# High Resolution Modeling of the Response of Tropical Cyclones to Climate Change

**Kerry Emanuel**

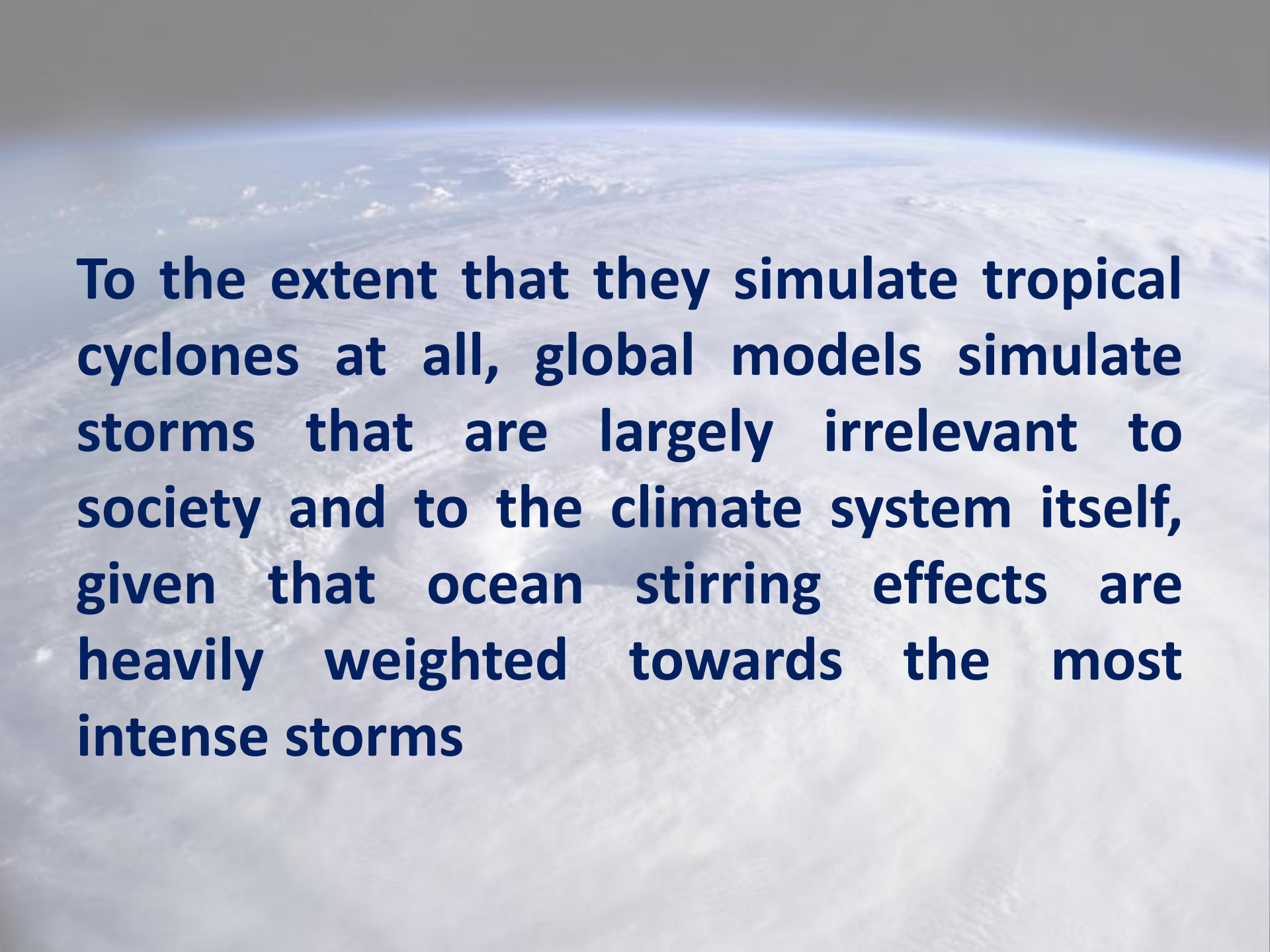**Massachusetts Institute of Technology**

The Problem:

- **Global models are far too coarse to simulate high intensity tropical cyclones**

- **Embedding regional models within global models introduces problems stemming from incompatibility of models, and even regional models are usually too coarse**
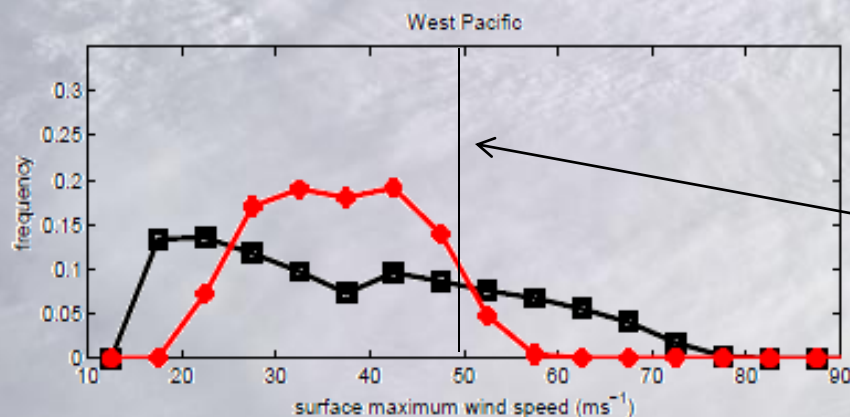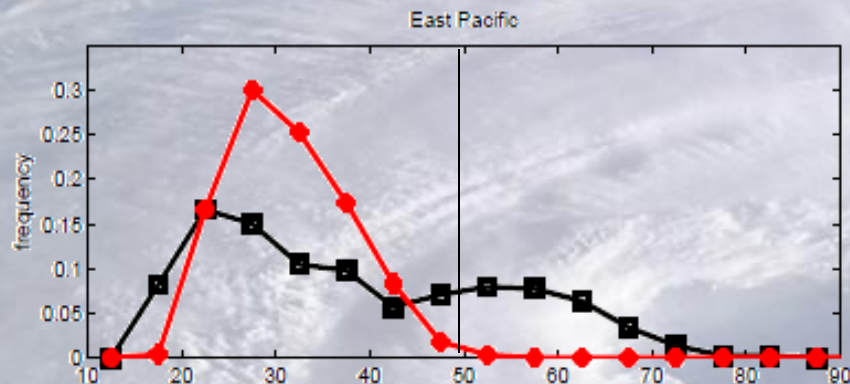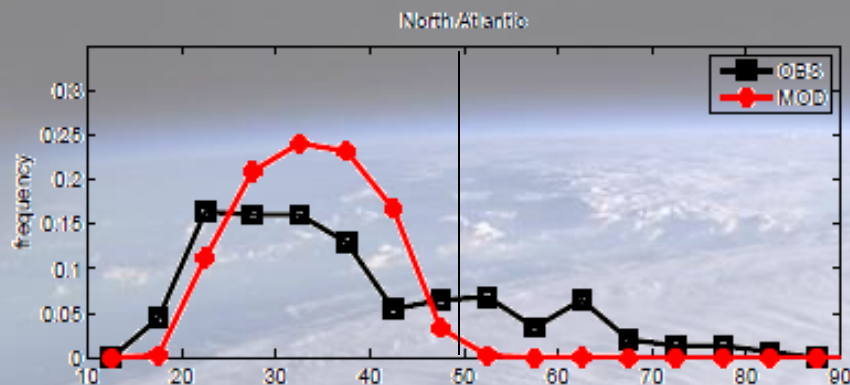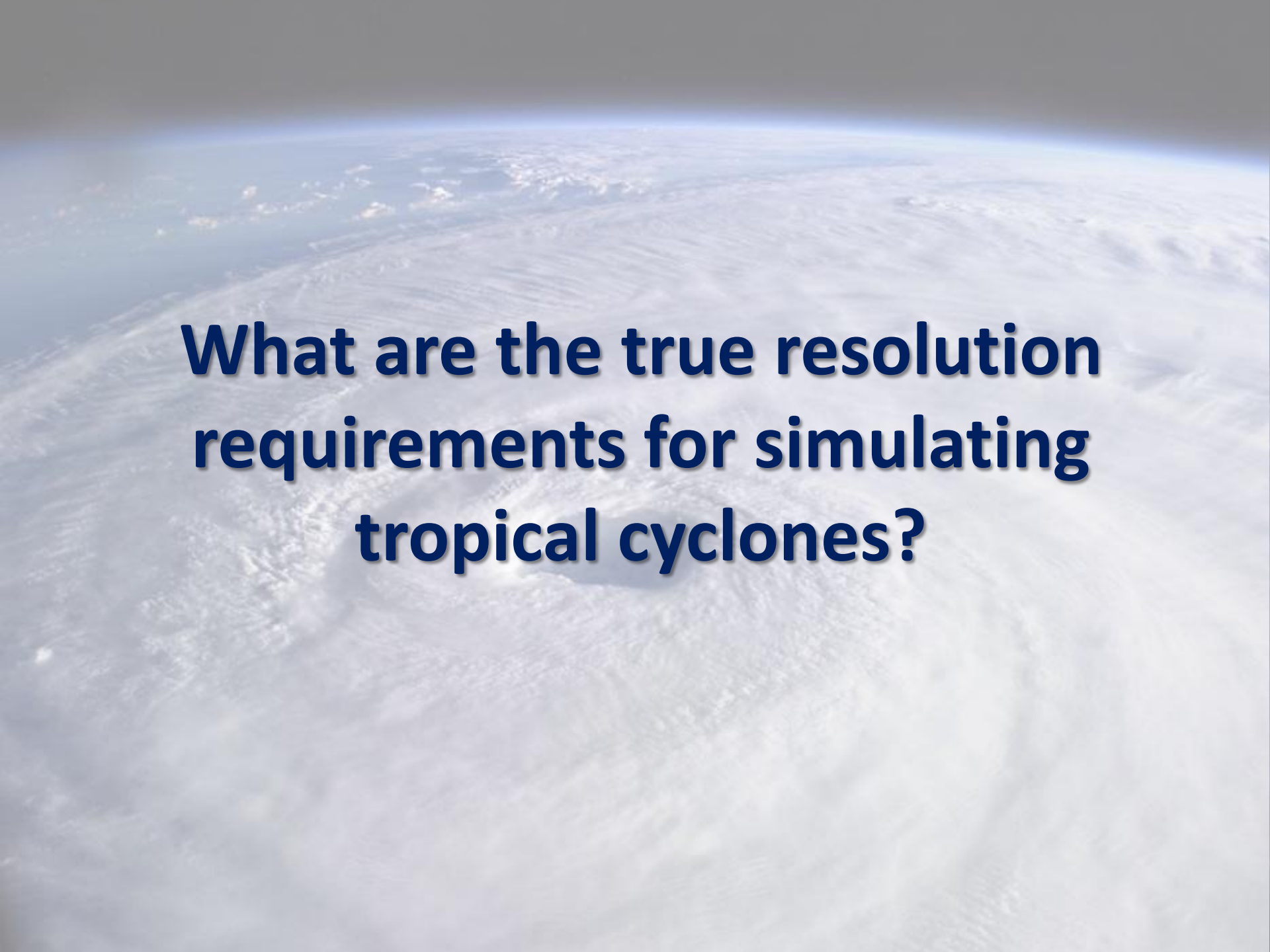
Histograms of Tropical Cyclone Intensity as Simulated by a Global Model with 50 km grid point spacing. (Courtesy Isaac Held, GFDL)

Category 3

U.S. Hurricane Damage, 1900-2004, Adjusted for Inflation, Wealth, and Population
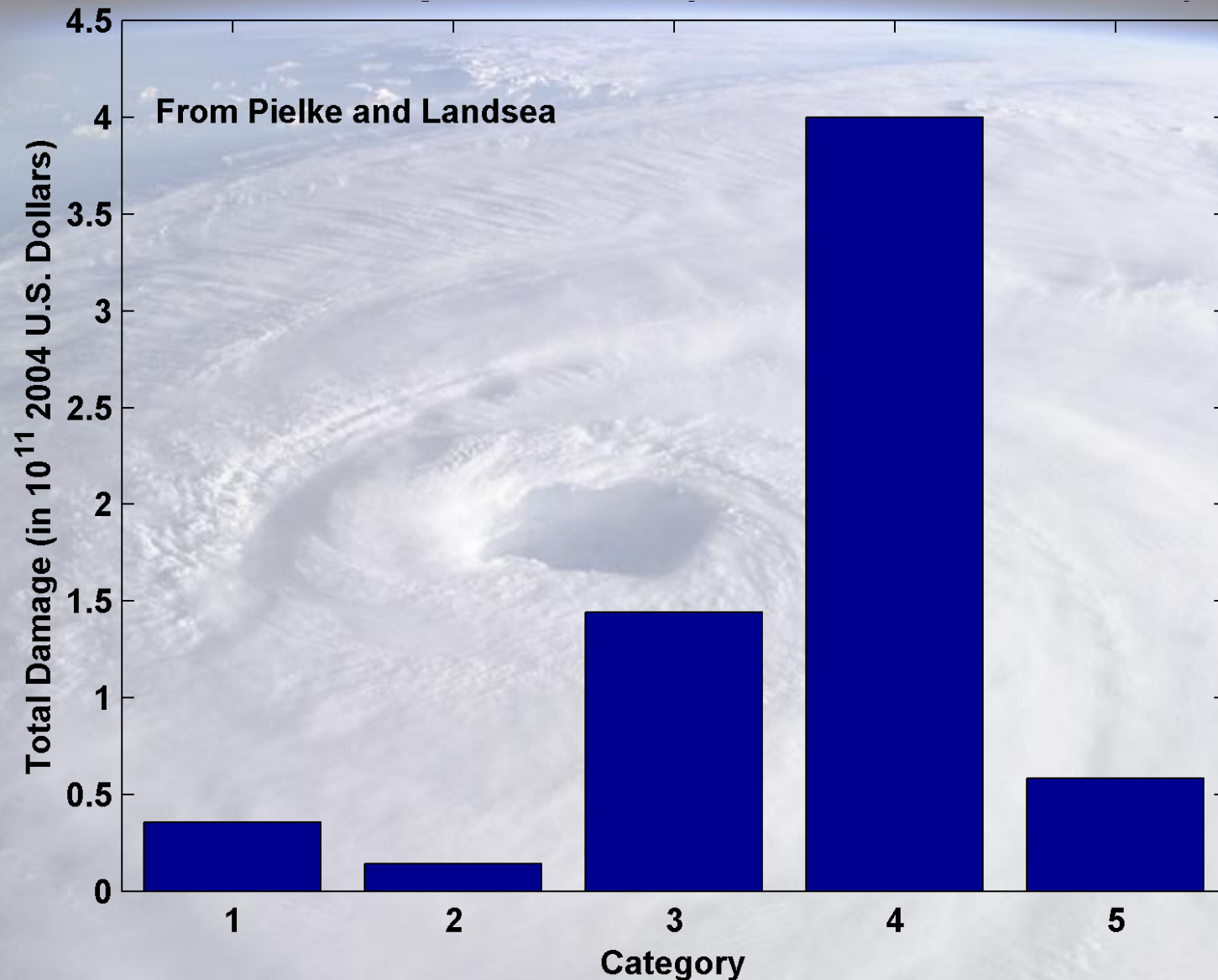
To the extent that they simulate tropical cyclones at all, global models simulate storms that are largely irrelevant to society and to the climate system itself, given that ocean stirring effects are heavily weighted towards the most intense storms

What are the true resolution requirements for simulating tropical cyclones?

Numerical convergence in an axisymmetric, nonhydrostatic model (Rotunno and Emanuel, 1987)
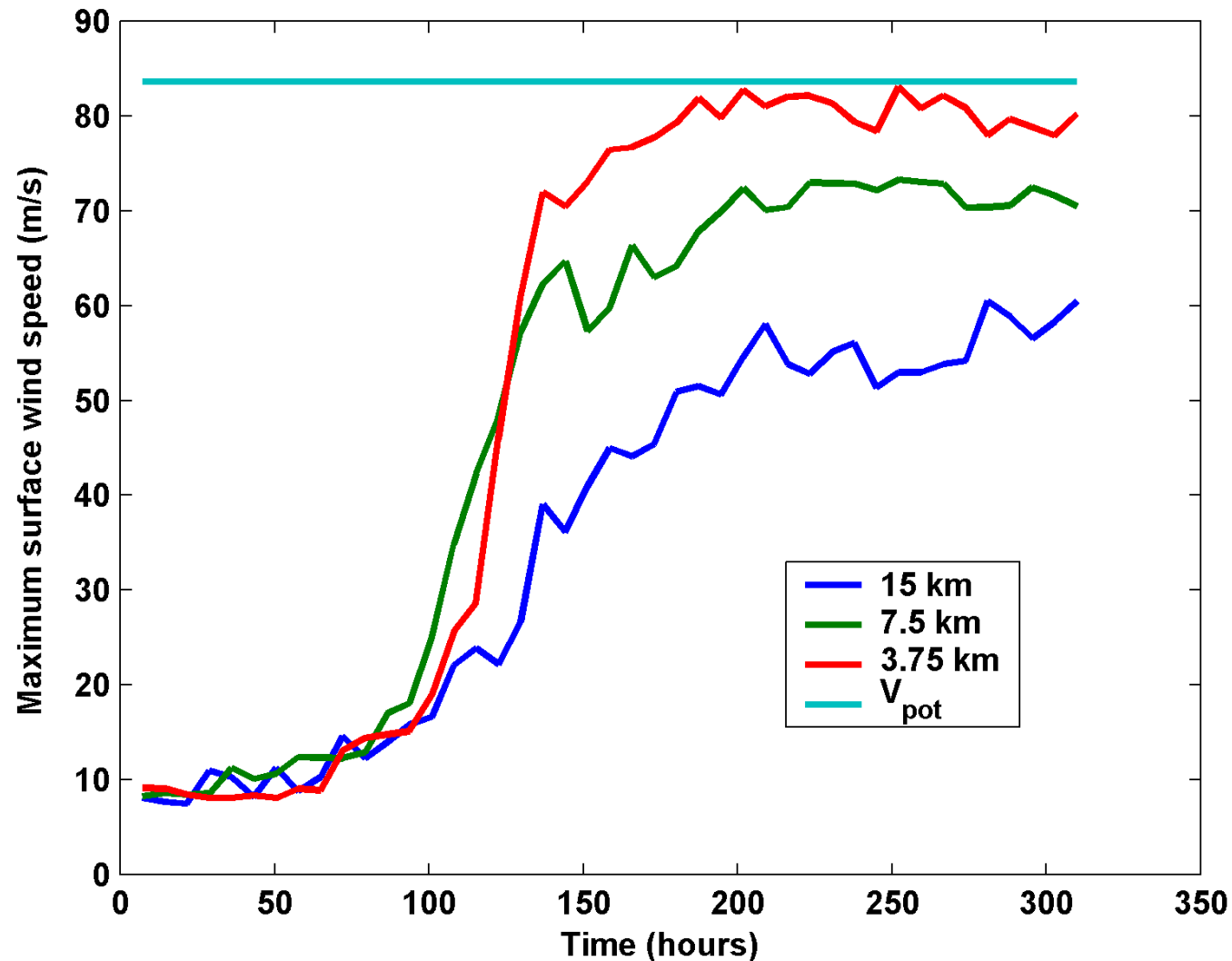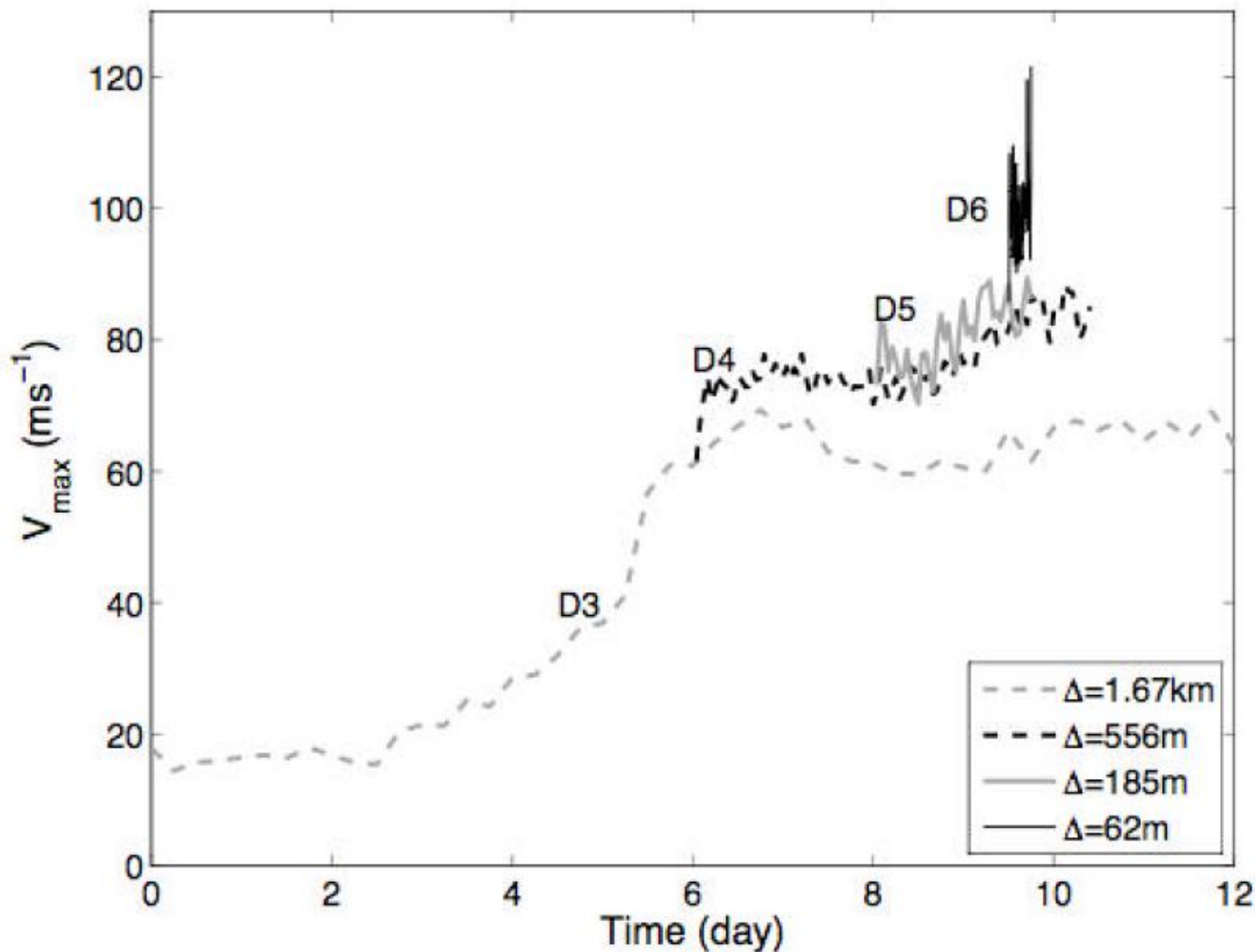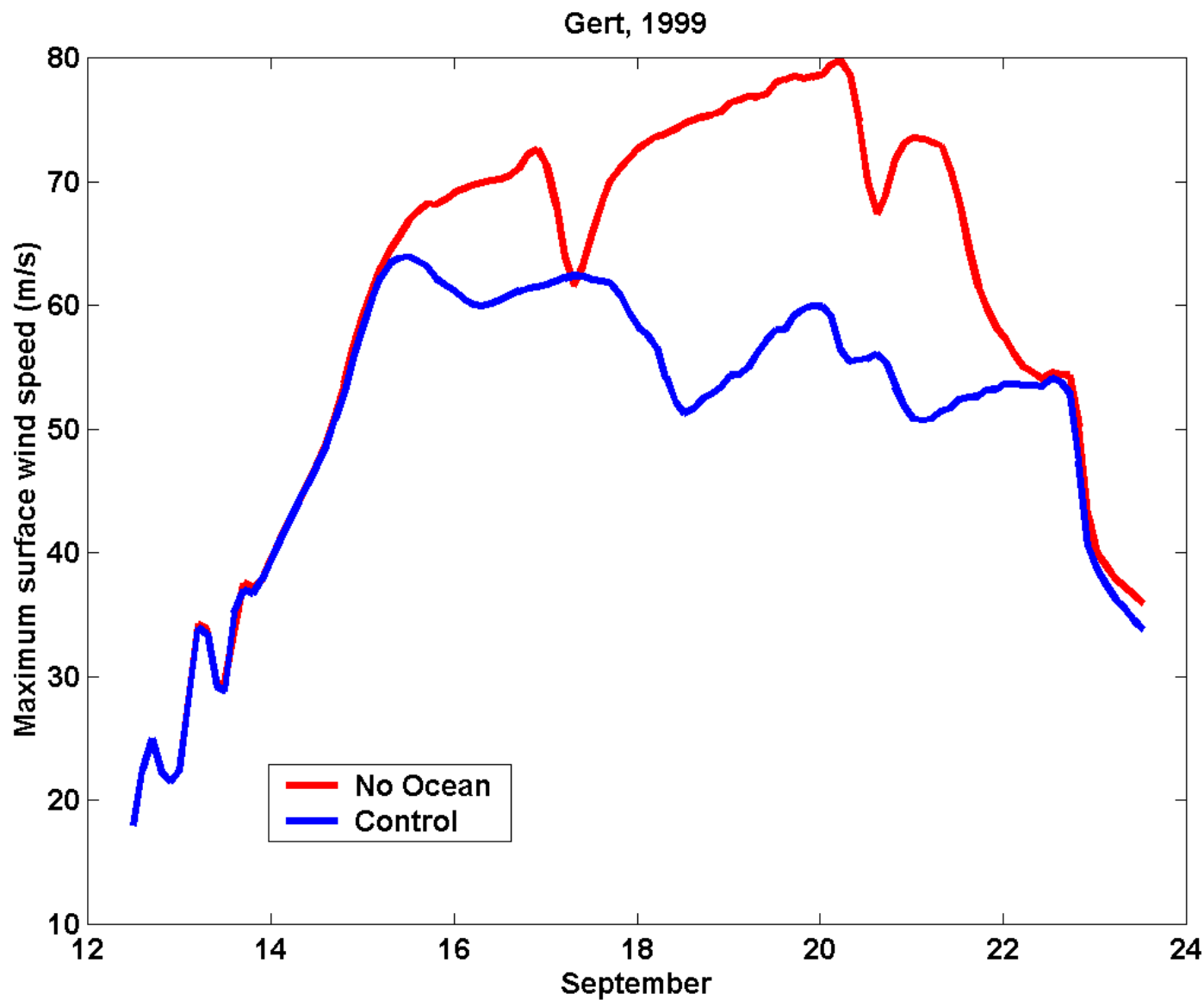
Figure courtesy of Rich Rotunno

Evolution of peak wind speed in domain for three-dimensional simulations of tropical cyclones using a cloud-resolving, nonhydrostatic model

Another Major Problem with Using Global and/or Regional Models to Simulate Tropical Cyclones:

Model TCs are not coupled to the ocean

Comparing Fixed to Interactive SST:

Gert, 1999

Our Solution:

Drive a simple but very high resolution, coupled ocean-atmosphere TC model using boundary conditions supplied by the global model or reanalysis data set

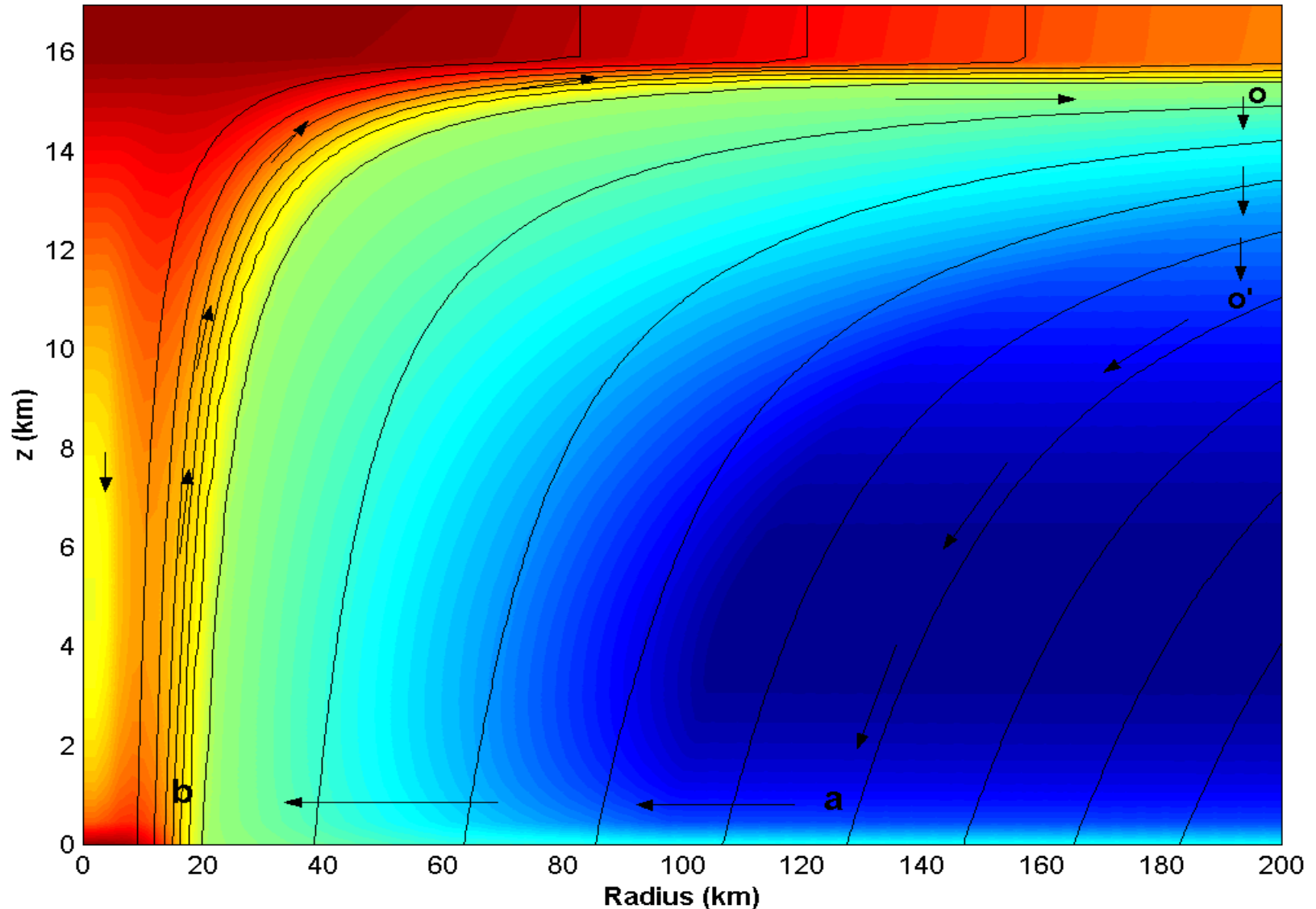# CHIPS: A Time-dependent, axisymmetric model phrased in R space

$$M = rV + \frac{1}{2}fr^2$$

$$\frac{1}{2}fR^2 \equiv M$$

- Hydrostatic and gradient balance above PBL
- Moist adiabatic lapse rates on M surfaces above PBL
- Boundary layer quasi-equilibrium
- Deformation-based radial diffusion

Detailed view of Entropy and Angular Momentum

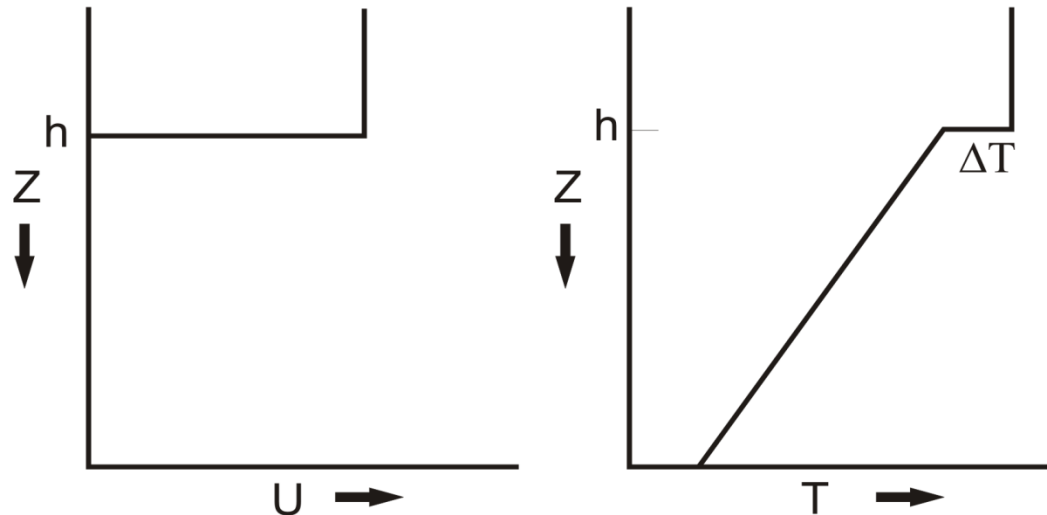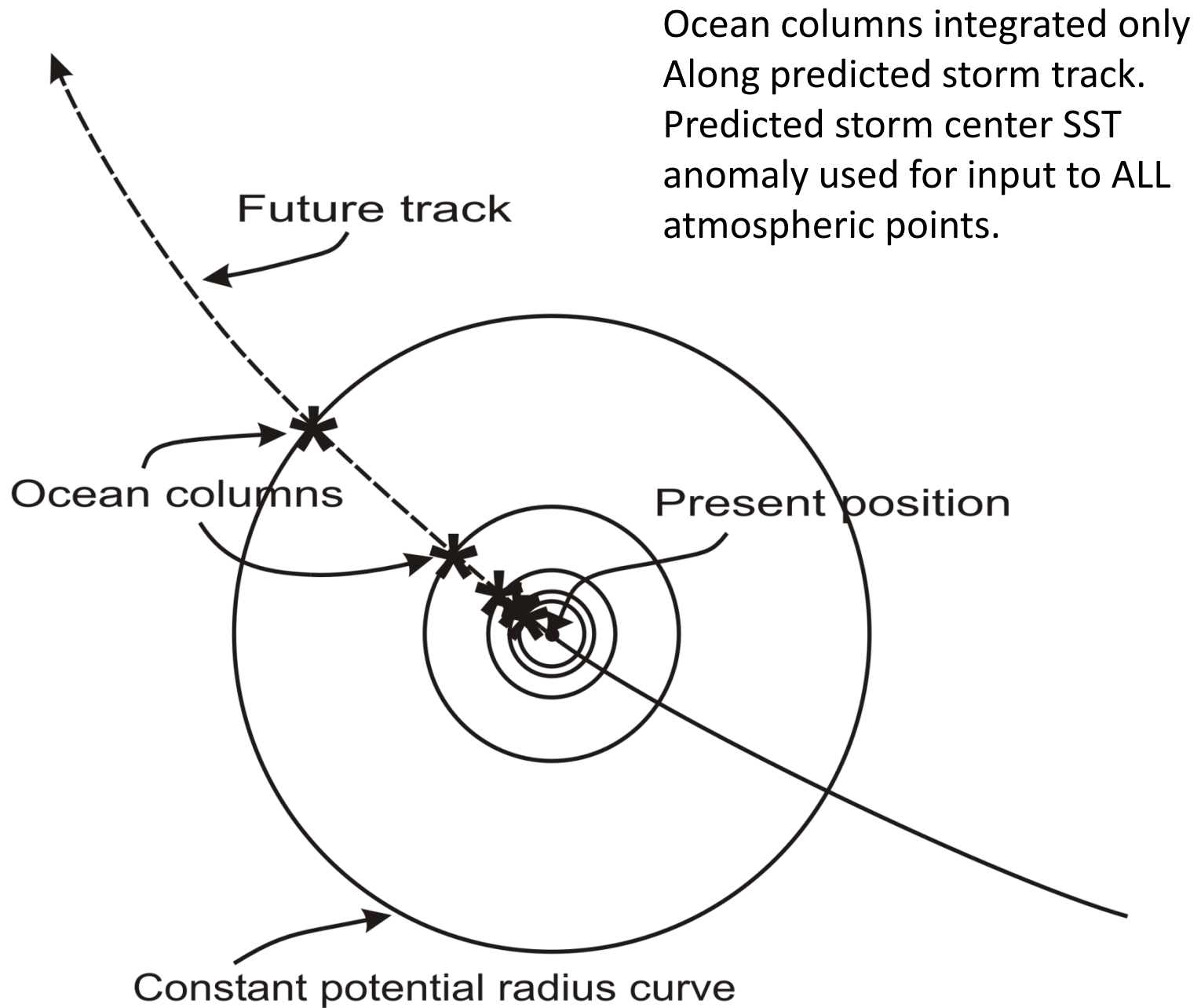Equivalent potential temperature (K), from 334.4955 to 373.3983

Ocean Component

(Schade, L.R., 1997: A physical interpreatation of SST-feedback.
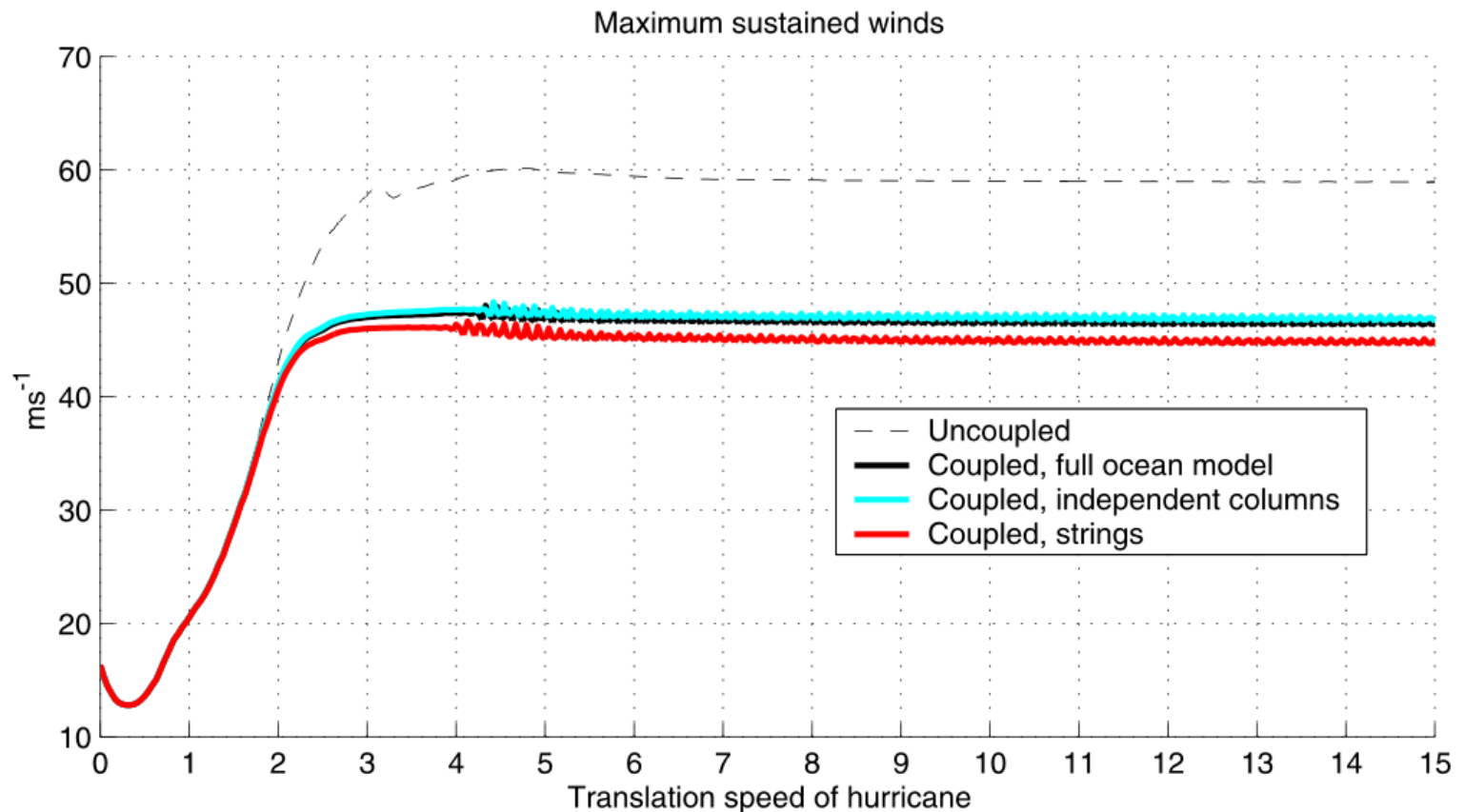Preprints of the 22nd Conf. on Hurr. Trop. Meteor., Amer. Meteor.
Soc., Boston, pgs. 439-440.)

- **Mixing by bulk-Richardson number closure**
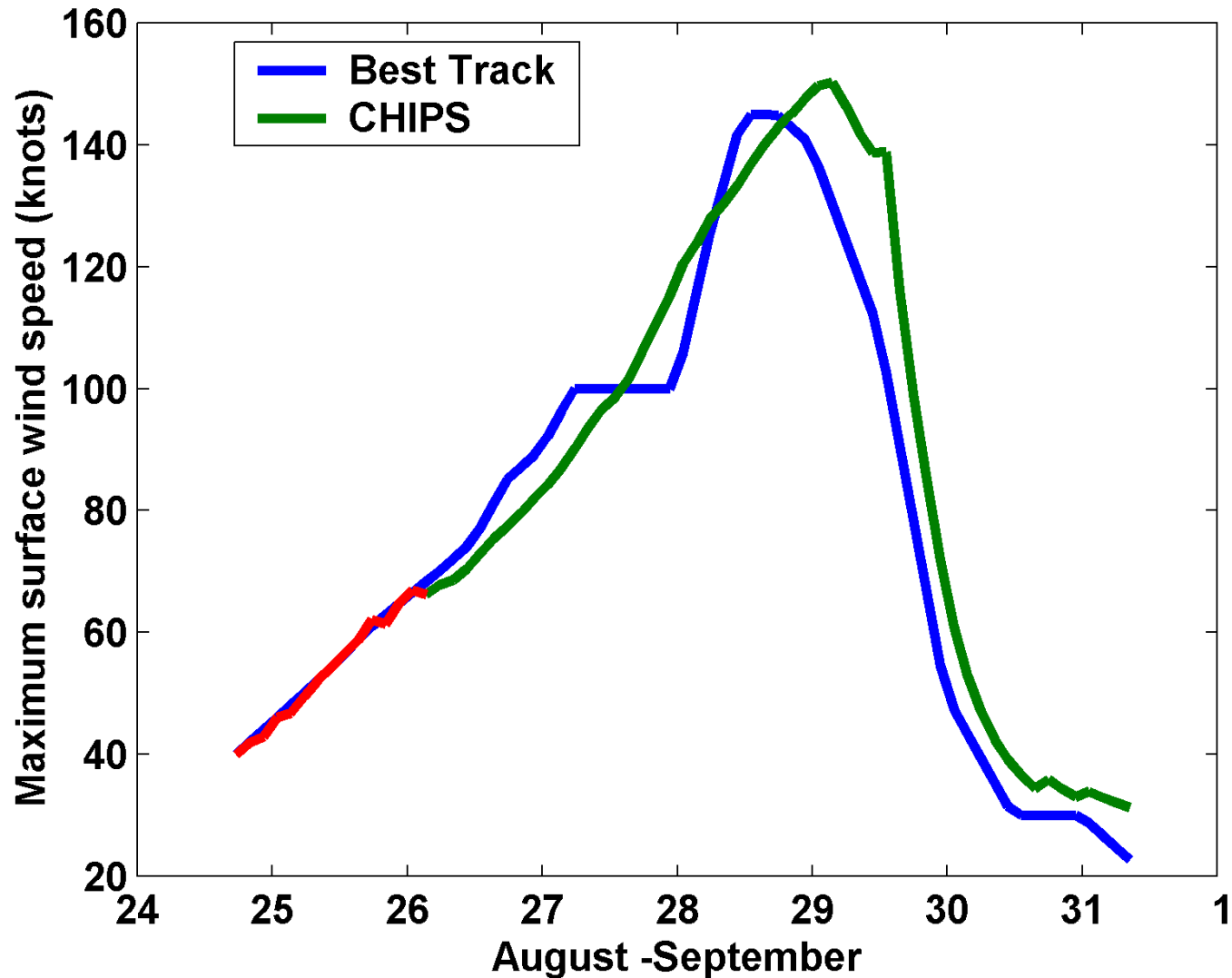- **Mixed-layer current driven by hurricane model surface wind**

Ocean columns integrated only
Along predicted storm track.
Predicted storm center SST
anomaly used for input to ALL
atmospheric points.

Future track

Ocean columns

Present position

Constant potential radius curve

Comparison with same atmospheric model coupled to 3-D ocean model; idealized runs:
Full model (black), string model (red)

Maximum sustained winds
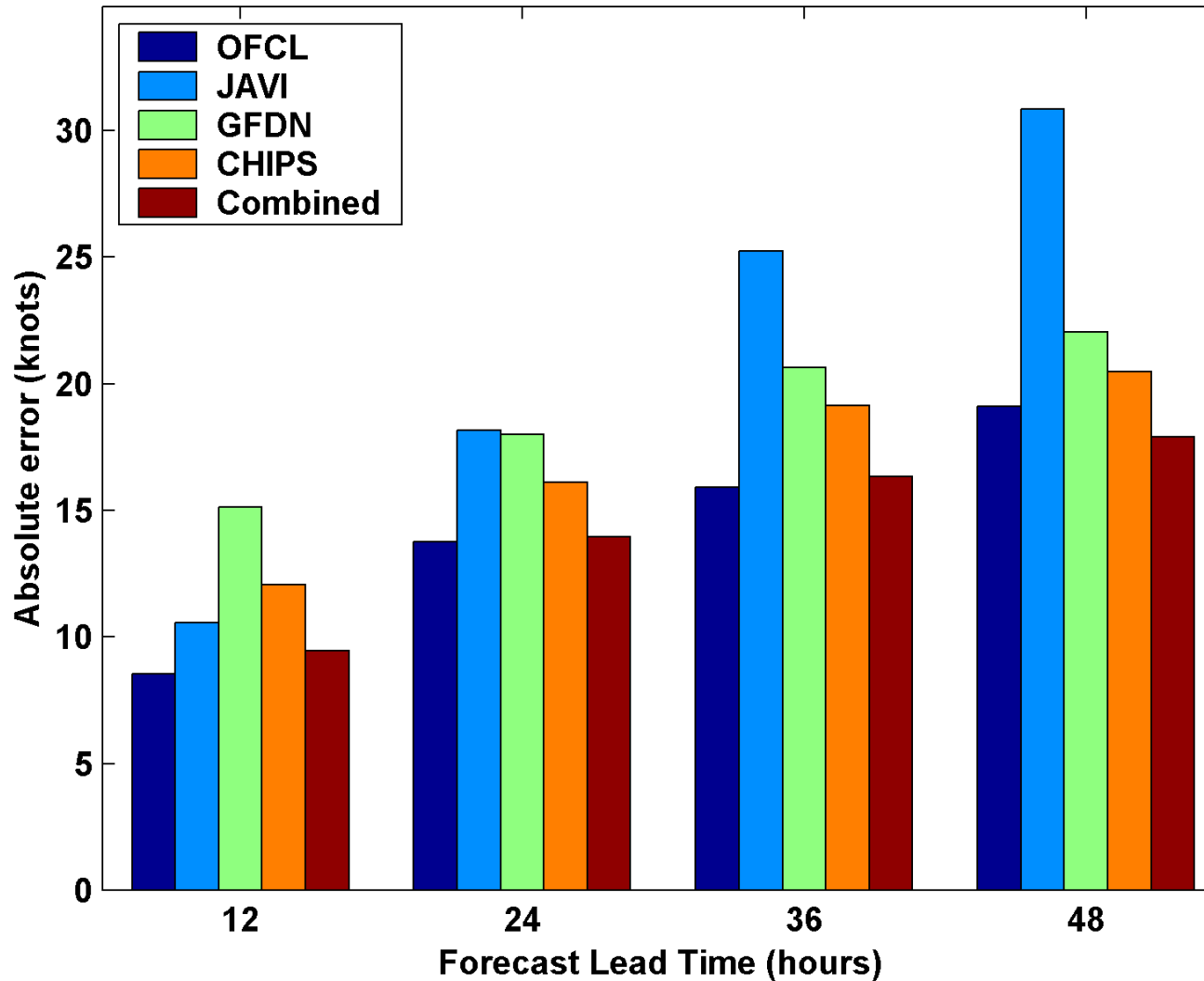
Legend:
- – – Uncoupled
- Coupled, full ocean model
- Coupled, independent columns
- Coupled, strings

y-axis: ms^{-1}
x-axis: Translation speed of hurricane

Hindcast of Katrina

Hurricane Katrina 2005

Comparison to Skill of Other Models

Southern Hemipshere, 2005-2006

Application to Assessing Tropical Cyclone Risk in a Changing Climate

Approach:

- **Step 1**: Seed each ocean basin with a very large number of weak, randomly located cyclones

- **Step 2**: Cyclones are assumed to move with the large scale atmospheric flow in which they are embedded, plus a correction for beta drift

- **Step 3**: Run the CHIPS model for each cyclone, and note how many achieve at least tropical storm strength

- **Step 4:** Using the small fraction of surviving events, determine storm statistics.

Details: Emanuel et al., BAMS, 2008

200 Synthetic U.S. Landfalling tracks (color coded by Saffir-Simpson Scale)
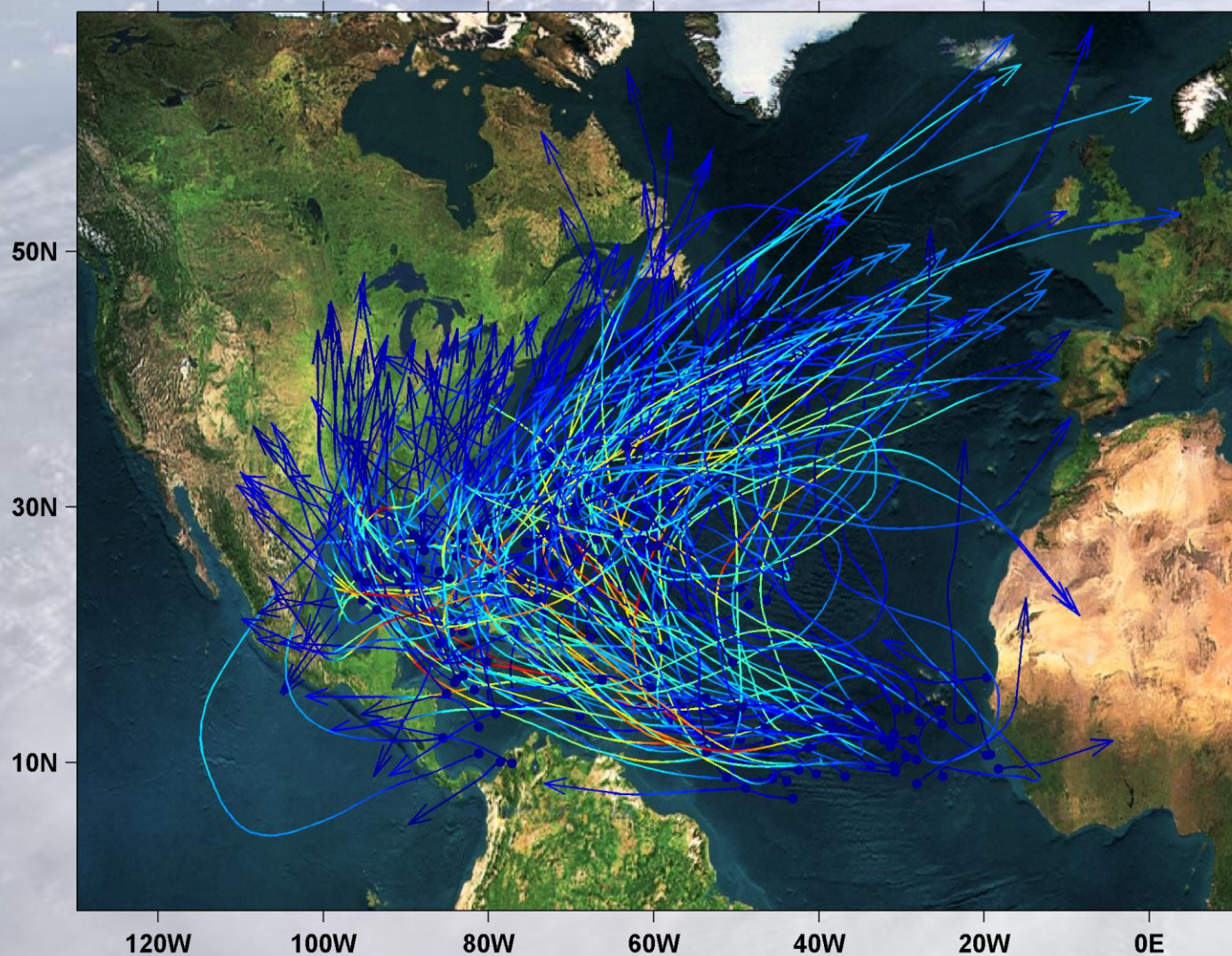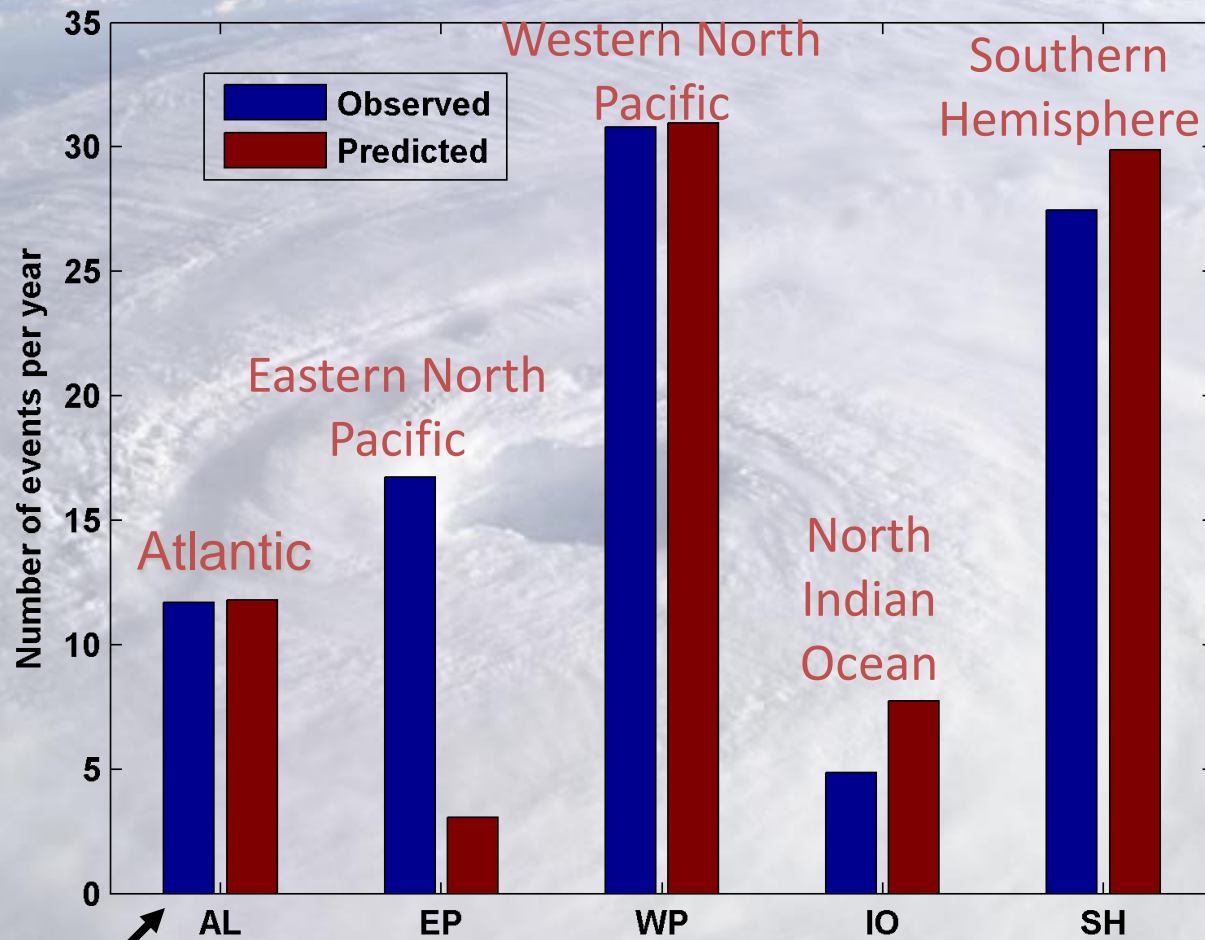
6-hour zonal displacements in region bounded by 10º and 30º N latitude, and 80º and 30º W longitude, using only post-1970 hurricane data
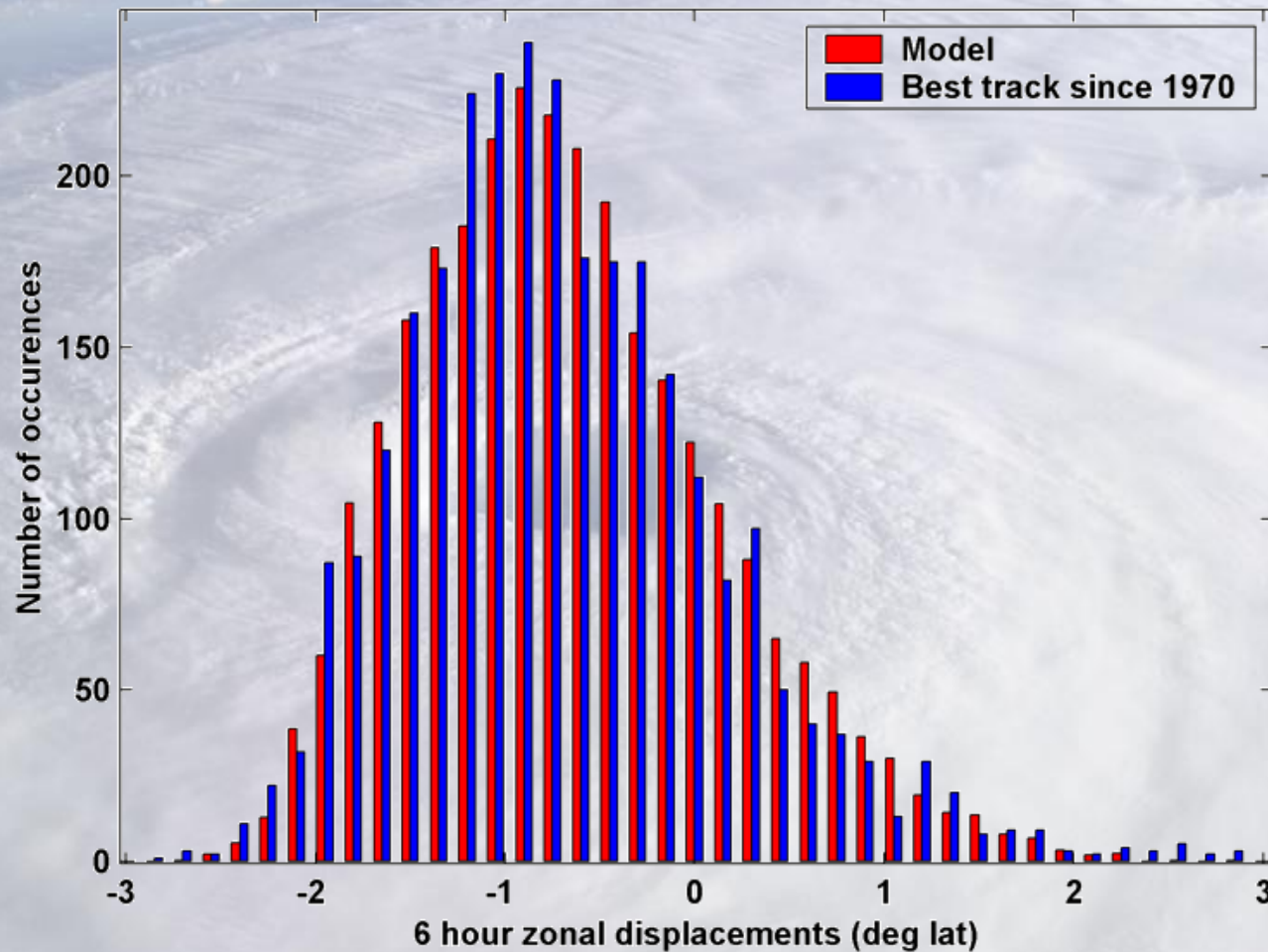
Calibration

- **Absolute genesis frequency calibrated to North Atlantic during the period 1980-2005**
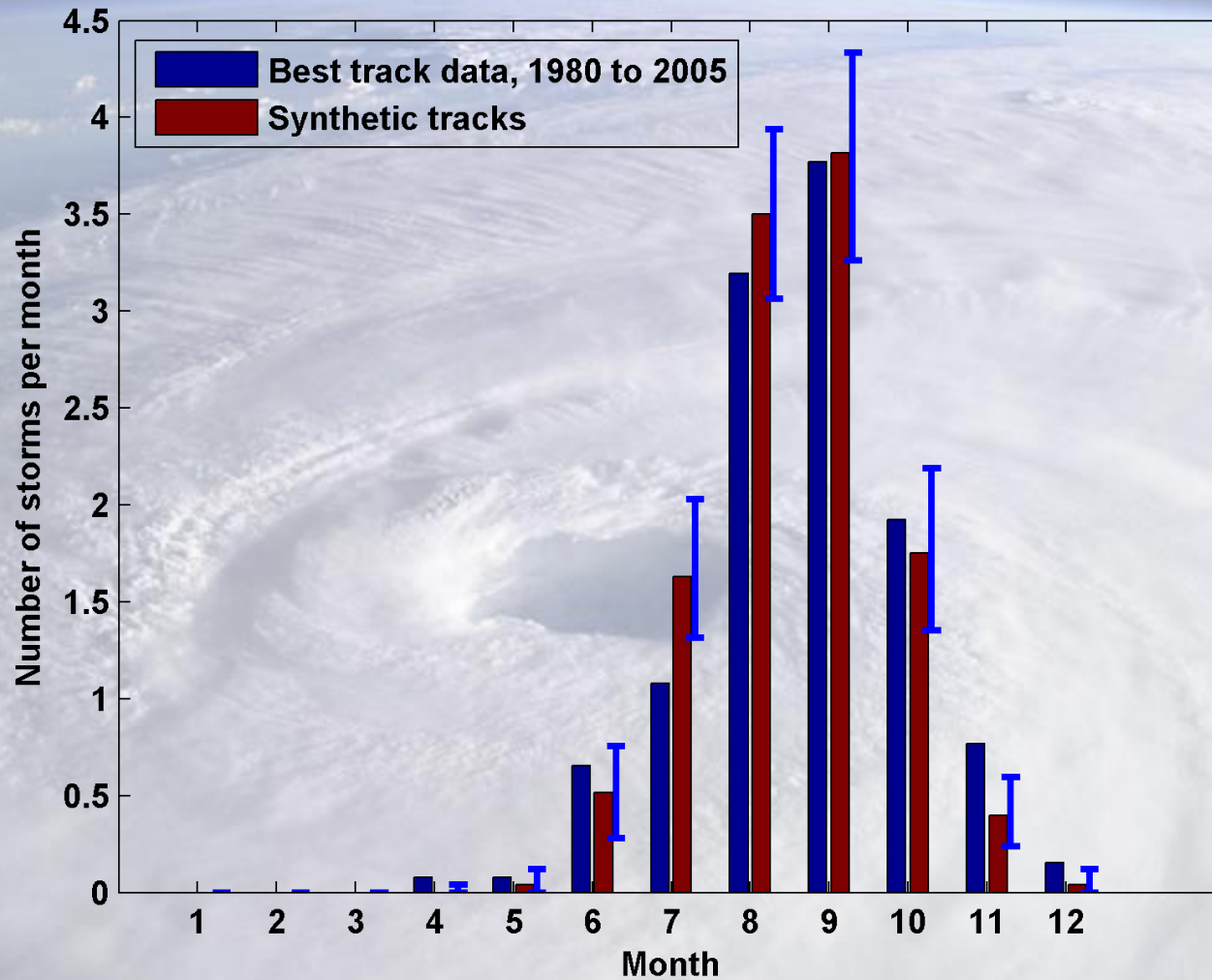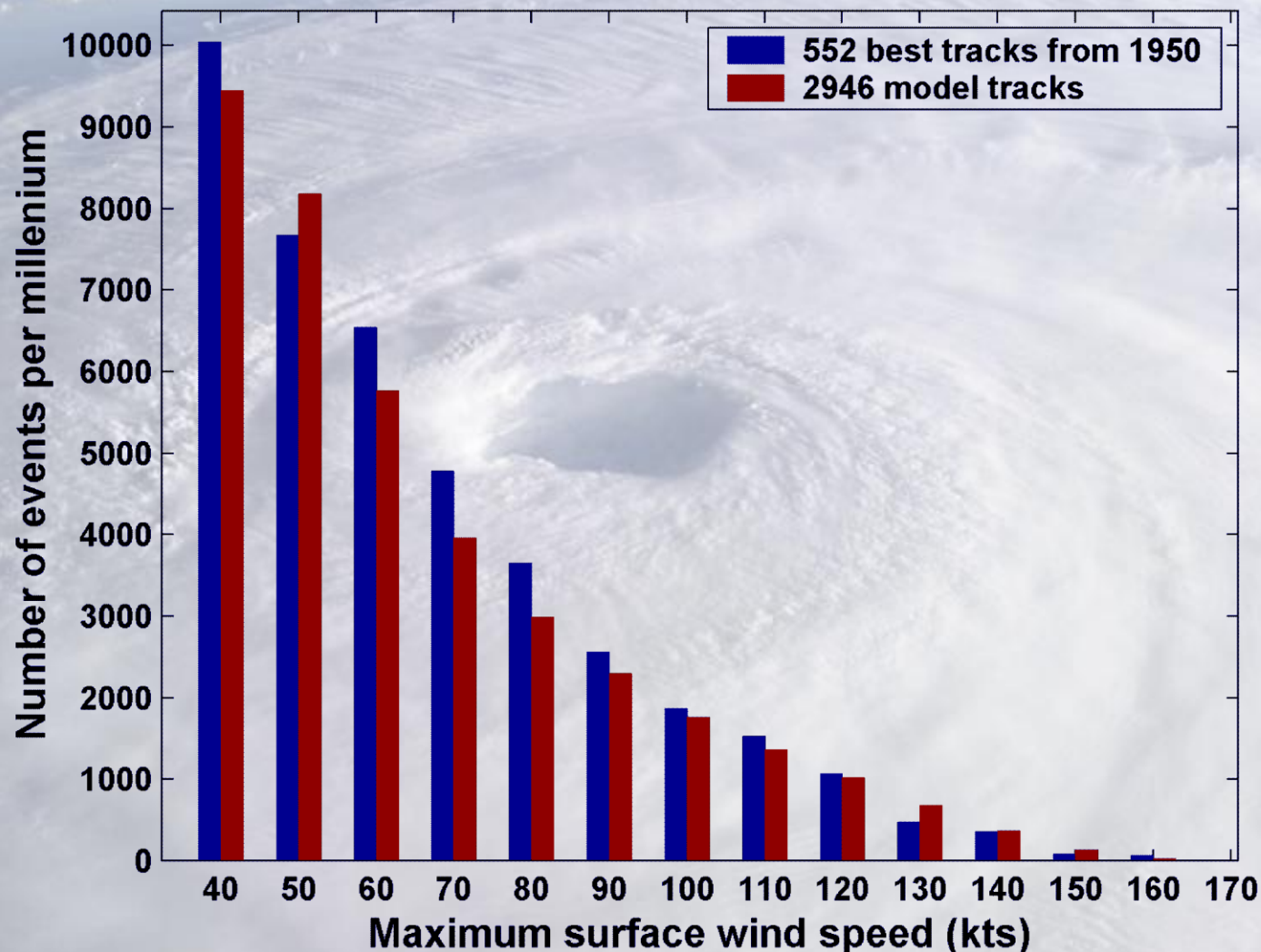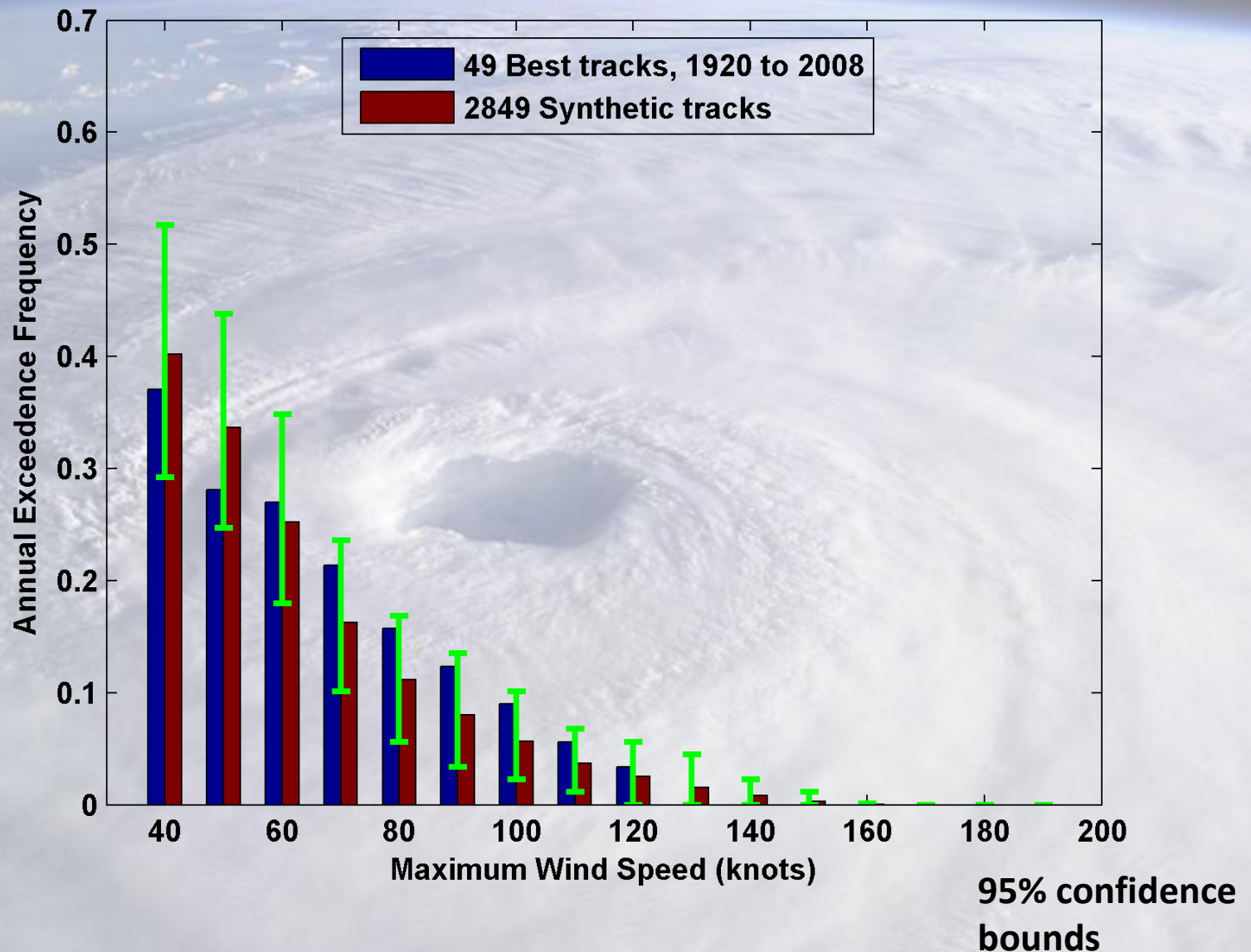
Genesis rates

Seasonal Cycles

North Atlantic

Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 2946 Synthetic Tracks

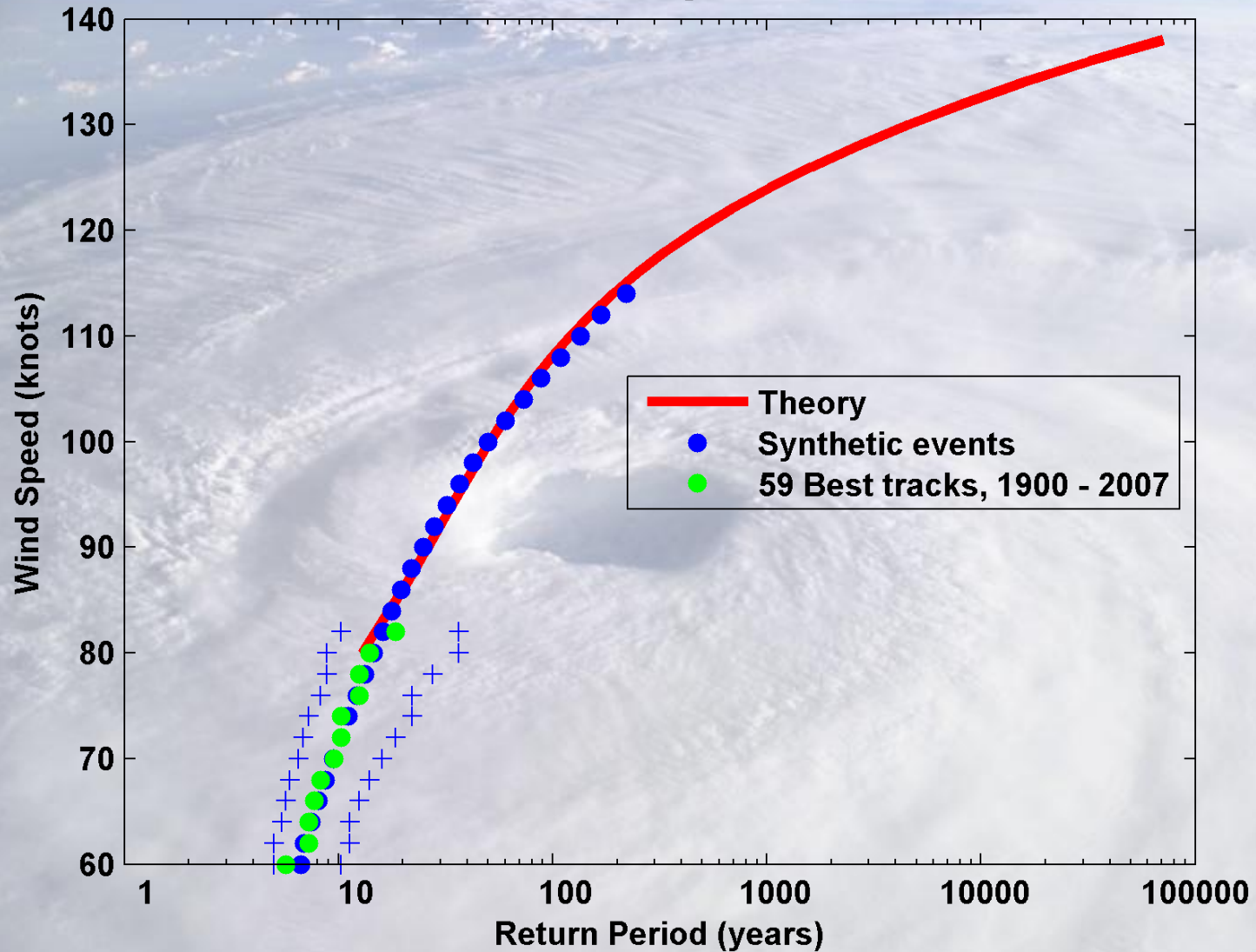# 3000 Tracks within 100 km of Miami

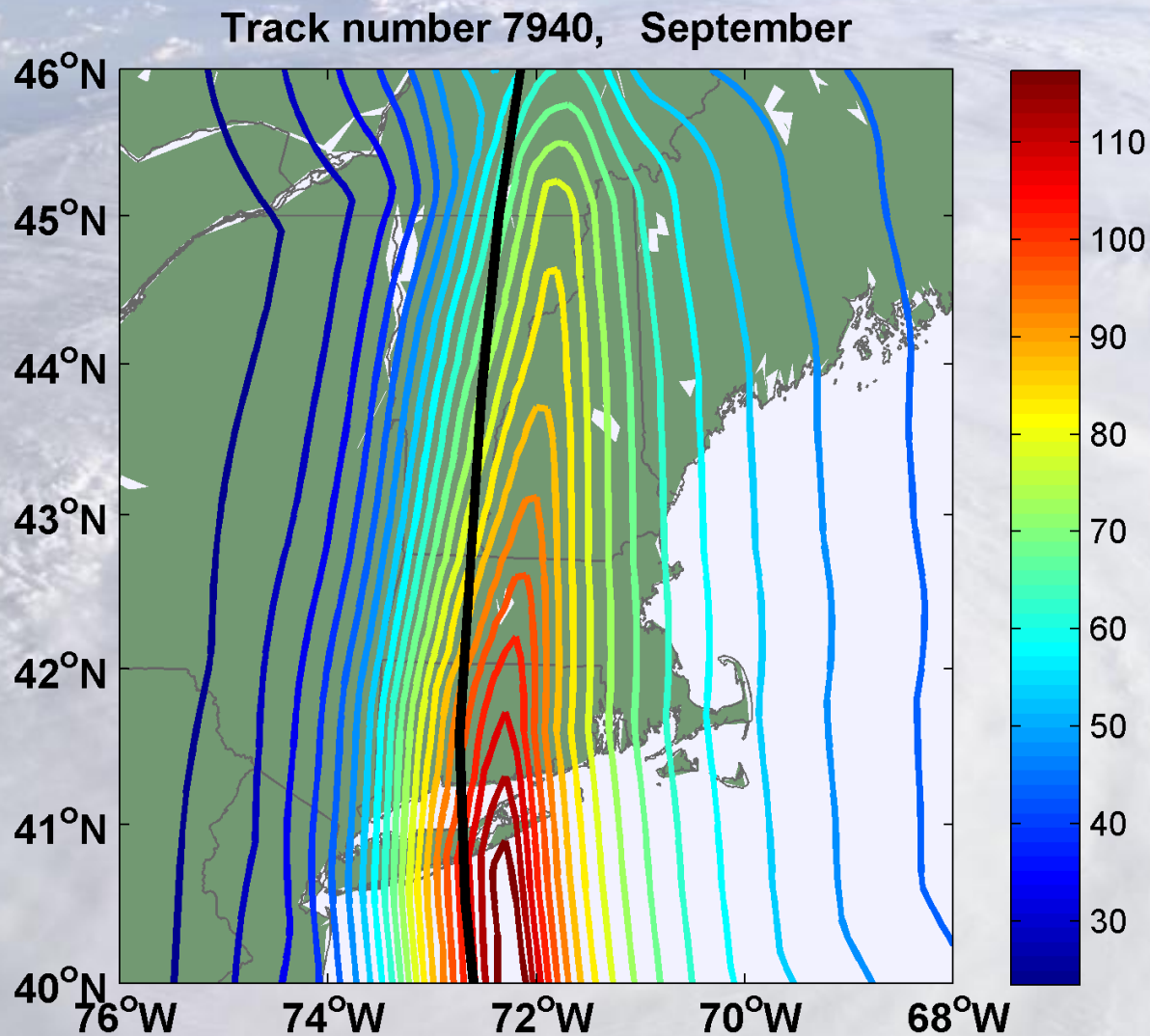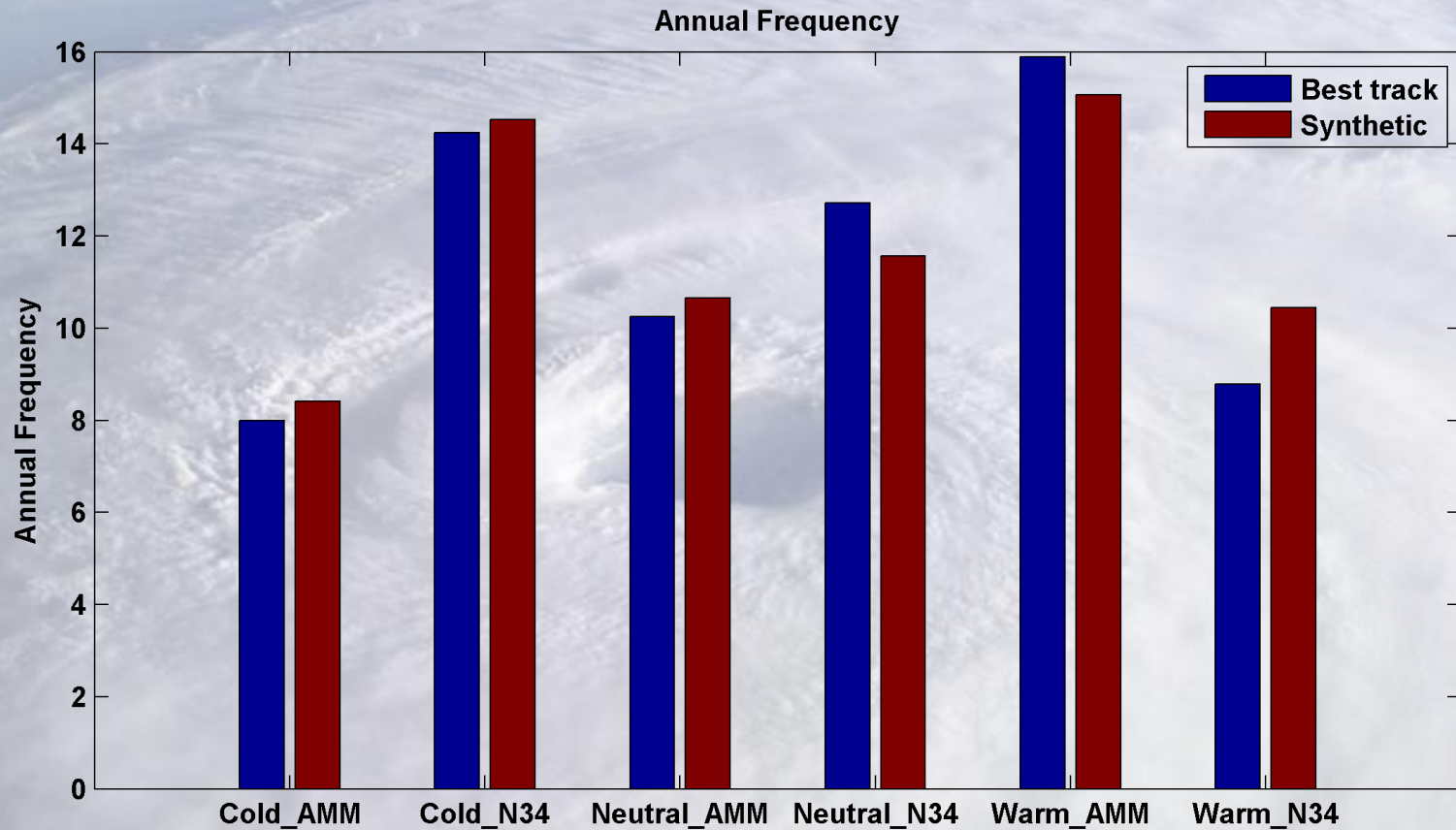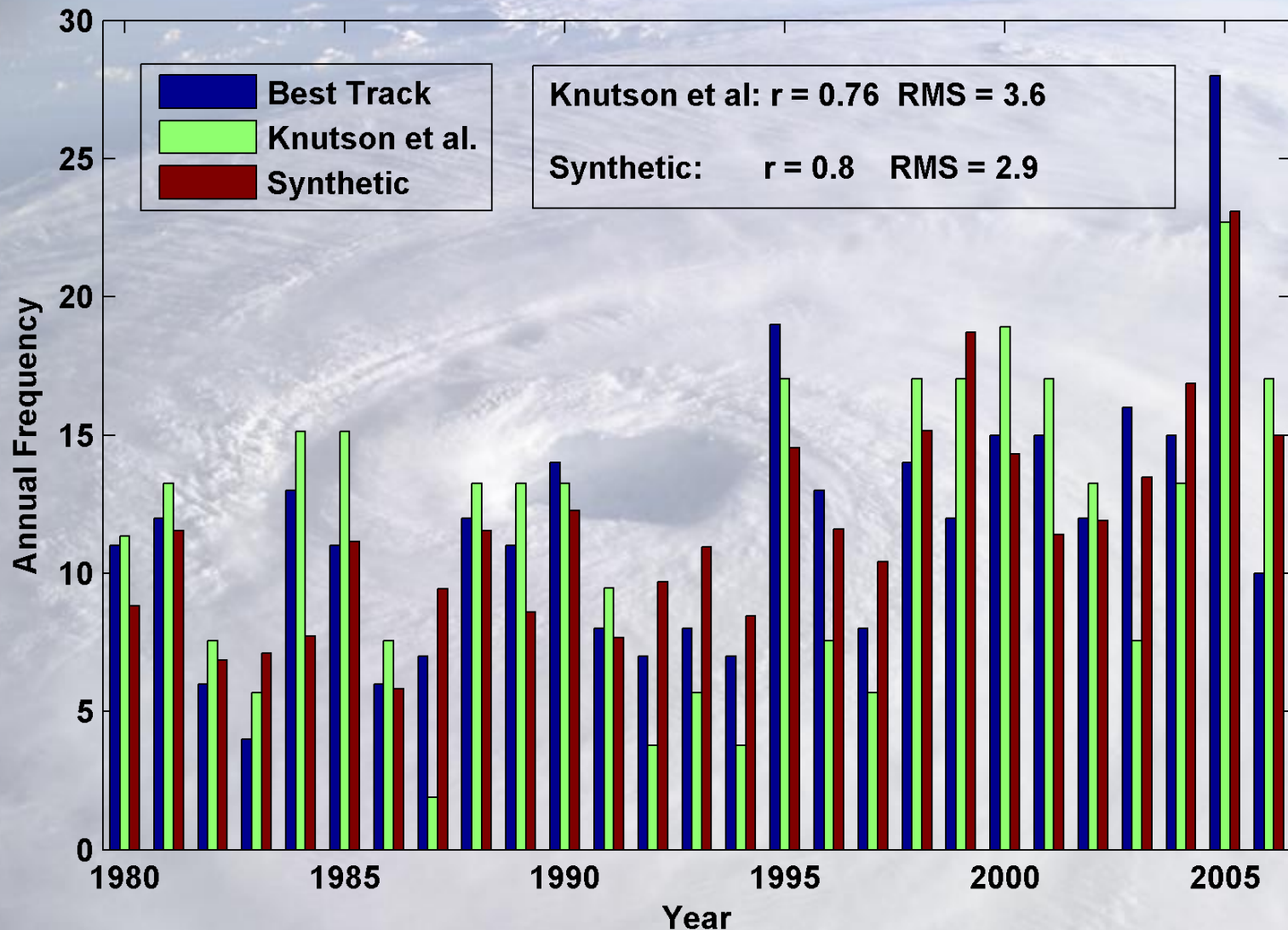95% confidence bounds

Return Periods

Sample Storm Wind Swath

Track number 7940,   September
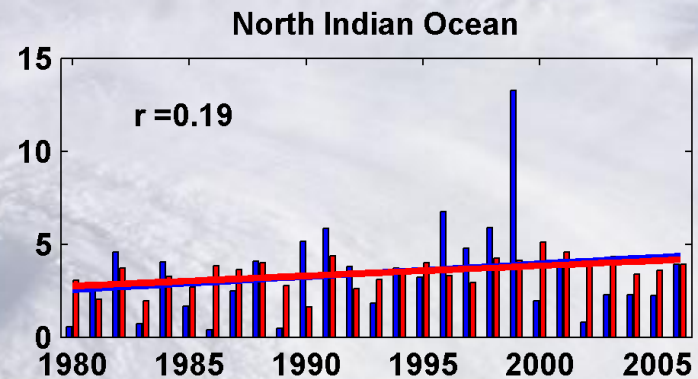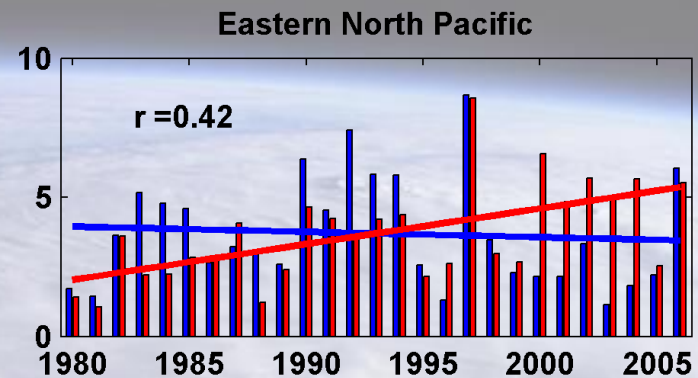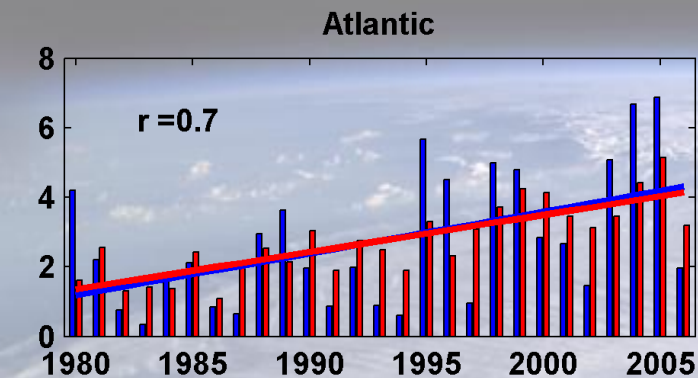
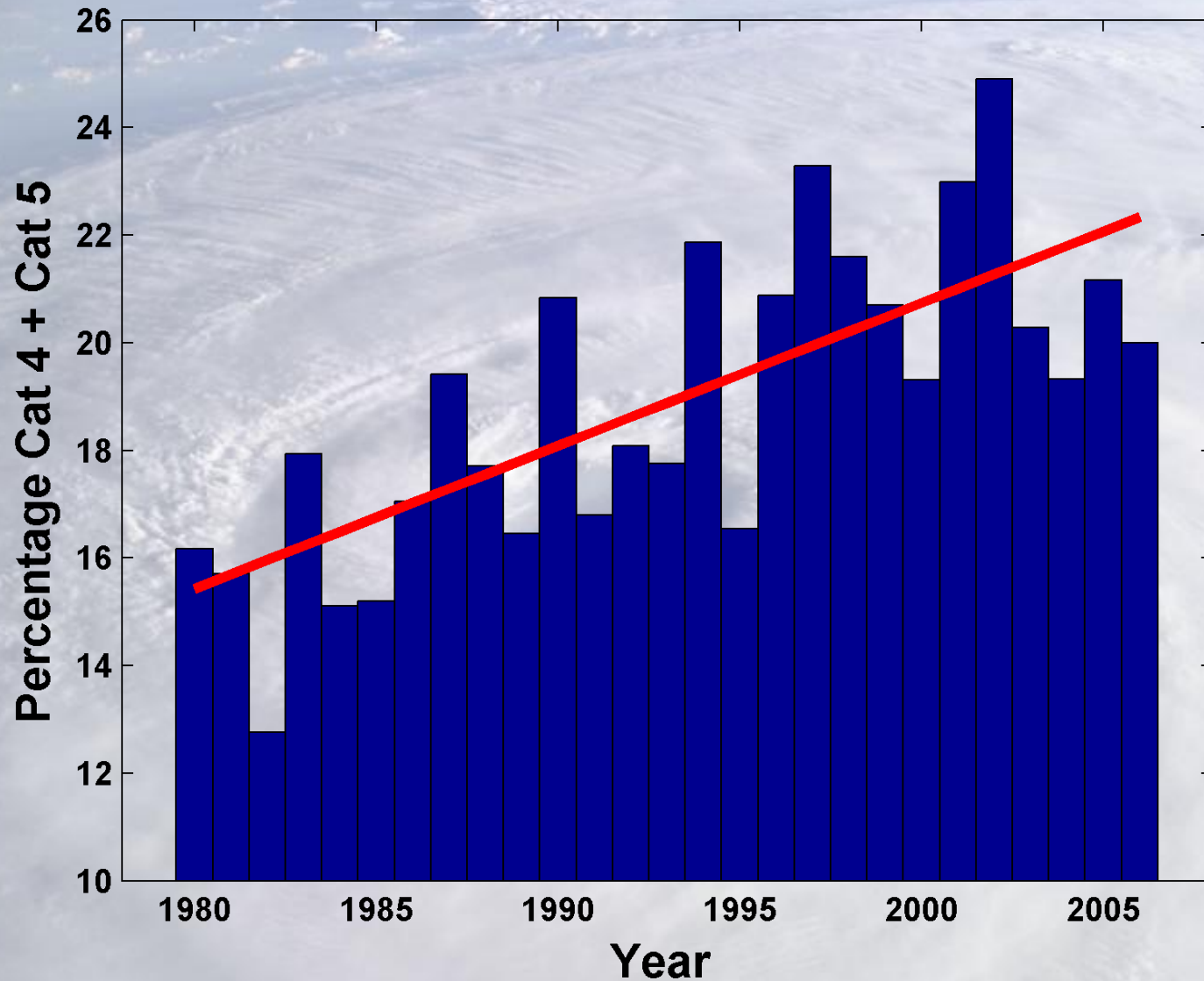# Captures effects of regional climate phenomena (e.g. ENSO, AMM)

Annual Frequency

Year by Year Comparison with Best Track and with Knutson et al., 2007

Simulated vs. Observed Power Dissipation Trends, 1980-2006
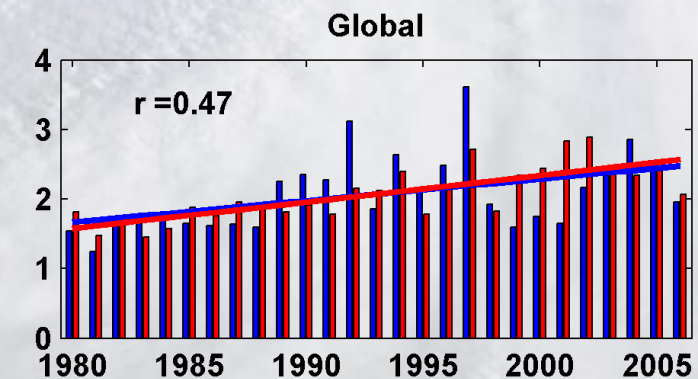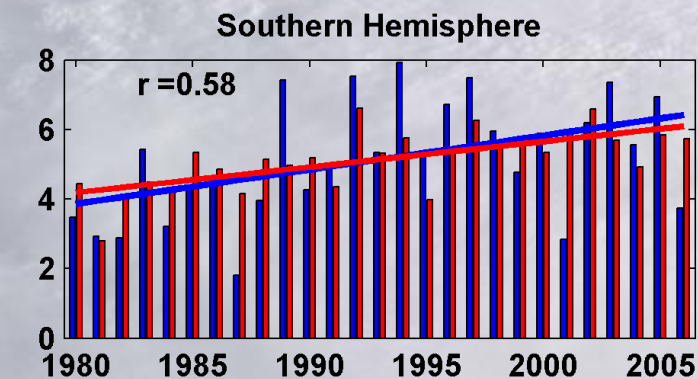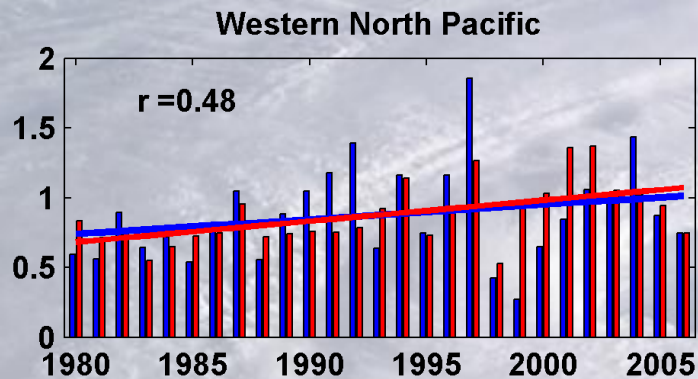
# Global Percentage of Cat 4 & Cat 5 Storms

Now Use Daily Output from IPCC Models to Derive Wind Statistics, Thermodynamic State Needed by Synthetic Track Technique

Compare two simulations each from 7 IPCC models:

1. Last 20 years of 20th century simulations

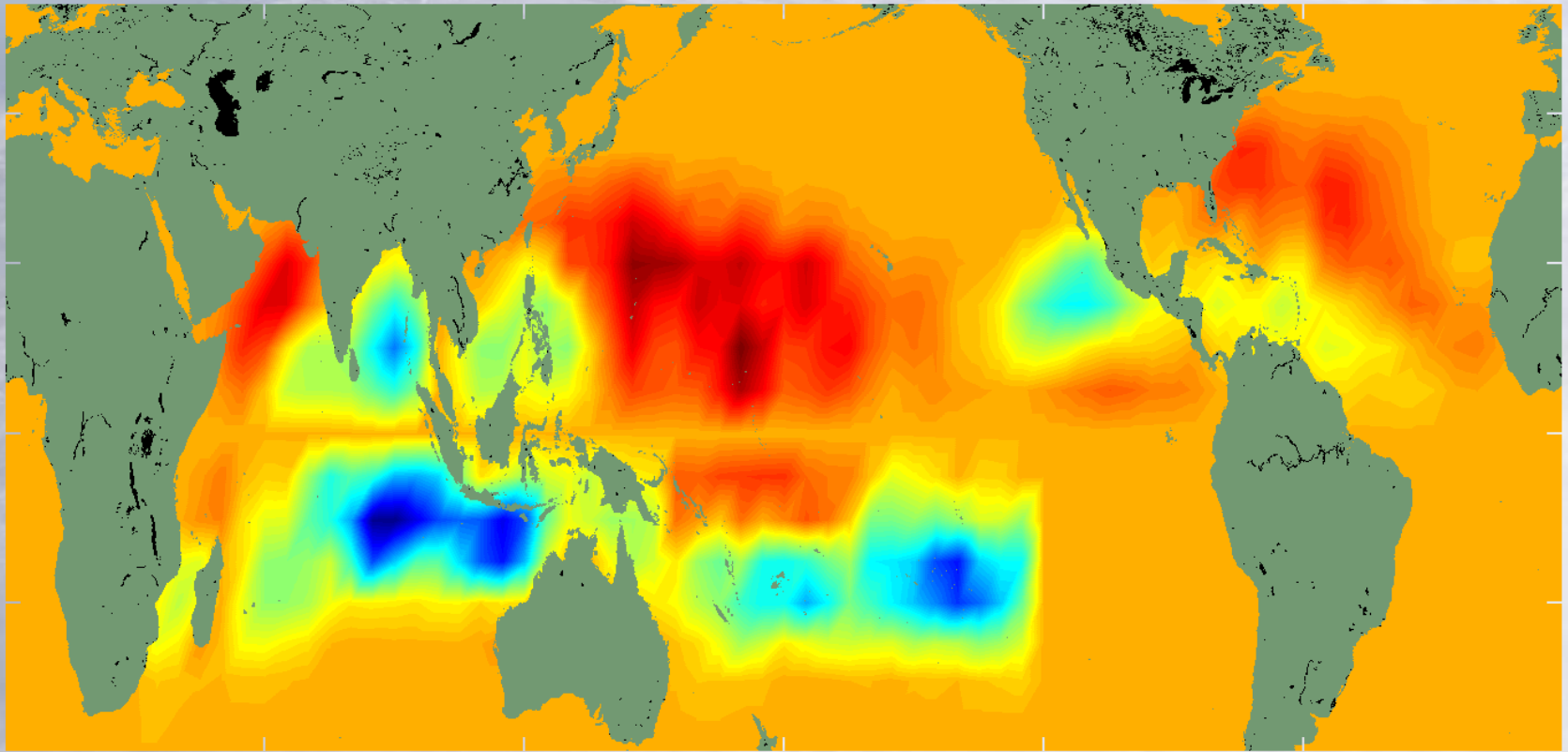**2.** Years 2180-2200 of IPCC Scenario A1b (CO_2 stabilized at 720 ppm)
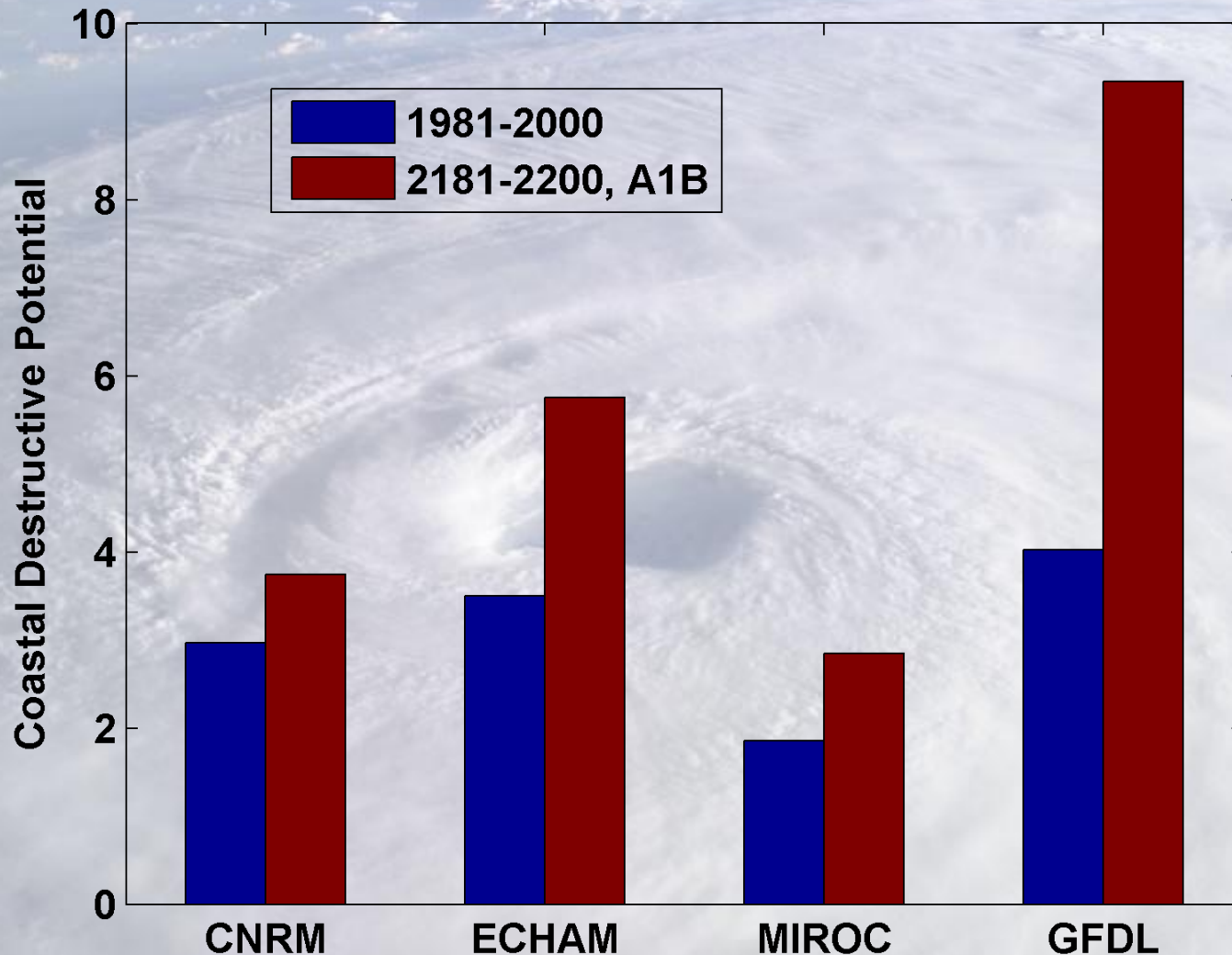
Basin-Wide Percentage Change in Power Dissipation
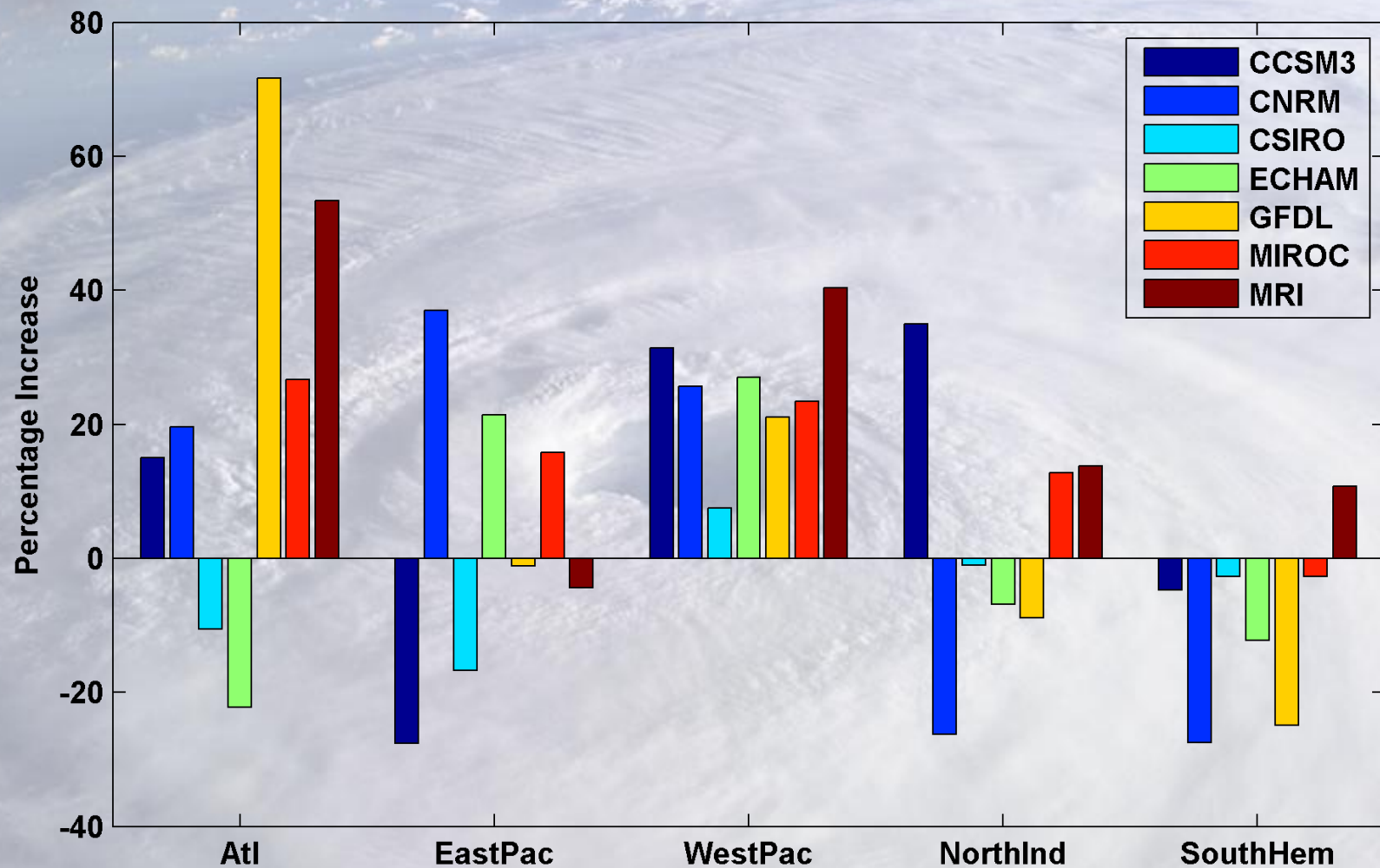
7 Model Consensus Change in Storm Frequency
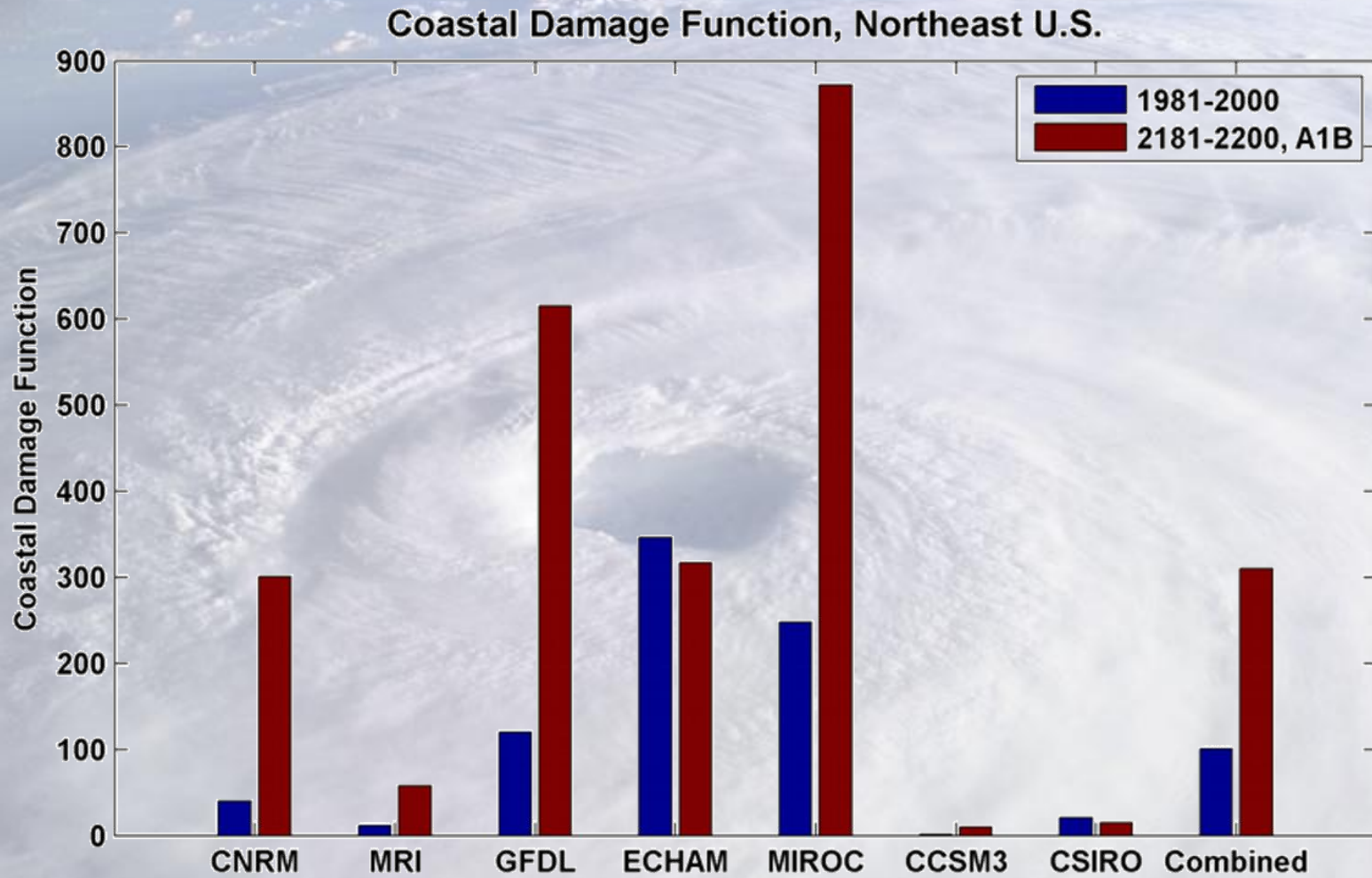

7-Model Consensus Change in Genesis Density

U.S. Coastal Damage Potential

Northeast U.S. Damage Function

Coastal Damage Function, Northeast U.S.

Change in Destructiveness of Hurricanes, Hispaniola

1000 Events Passing with 100 km of Santo Domingo

Legend:
- 1981-2000
- 2181-2200, A1B

Y-axis: Tropical Cyclone Destruction Index
X-axis: Global Climate Model (ECHAM, GFDL, MRI, CRNM)
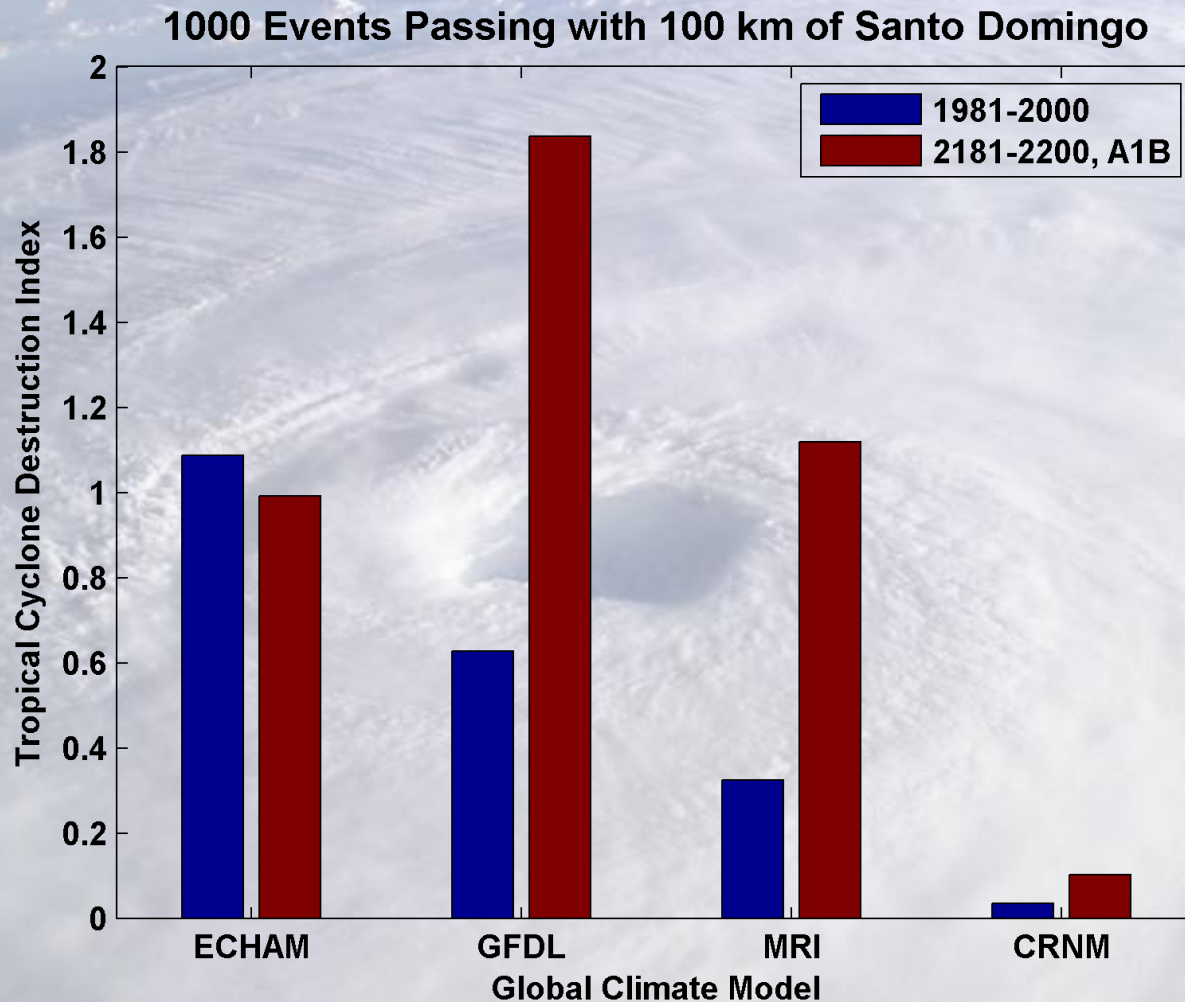
Change in Landslide Risk

Landslide Frequency based on 1000 Events near Santo Domingo
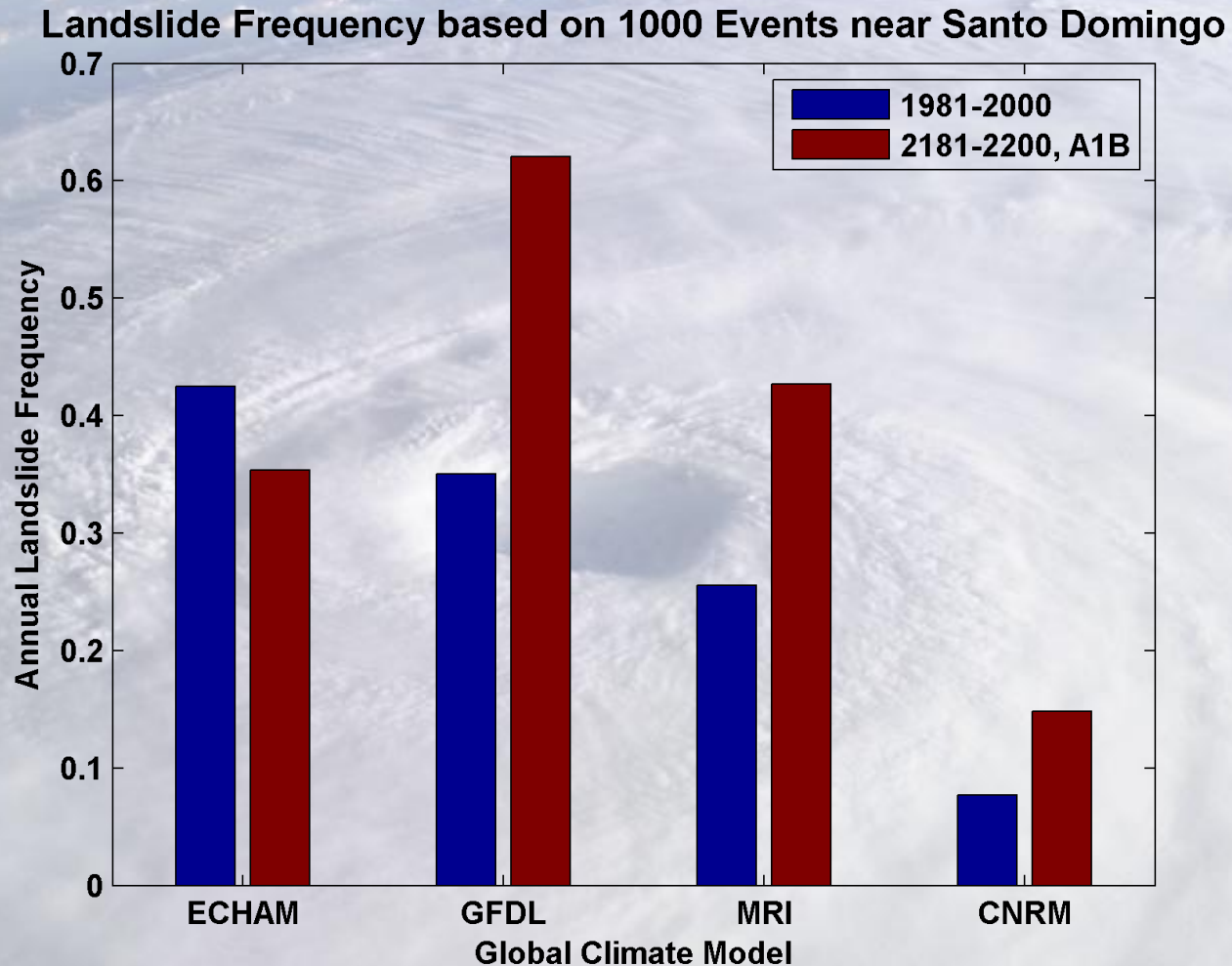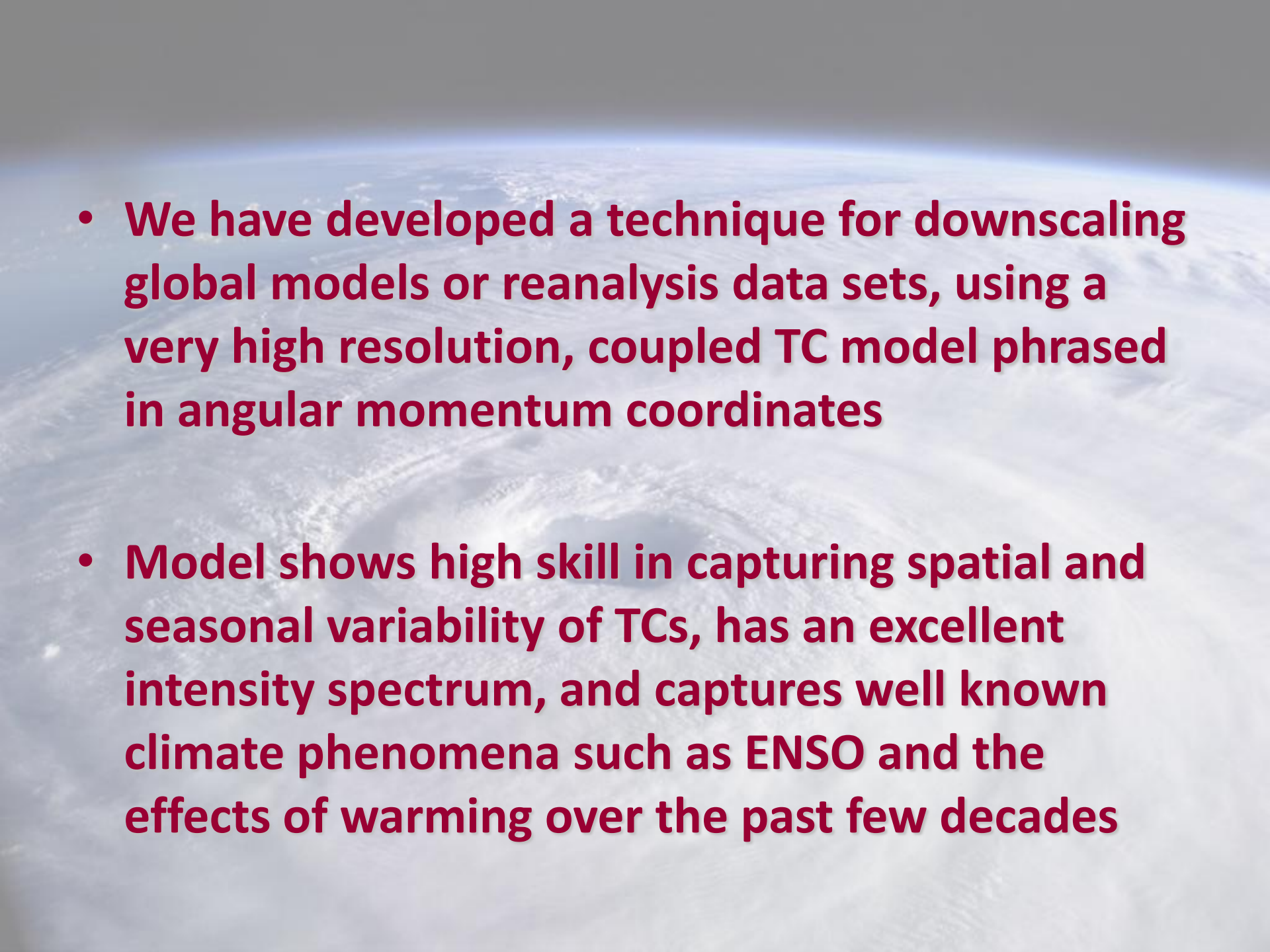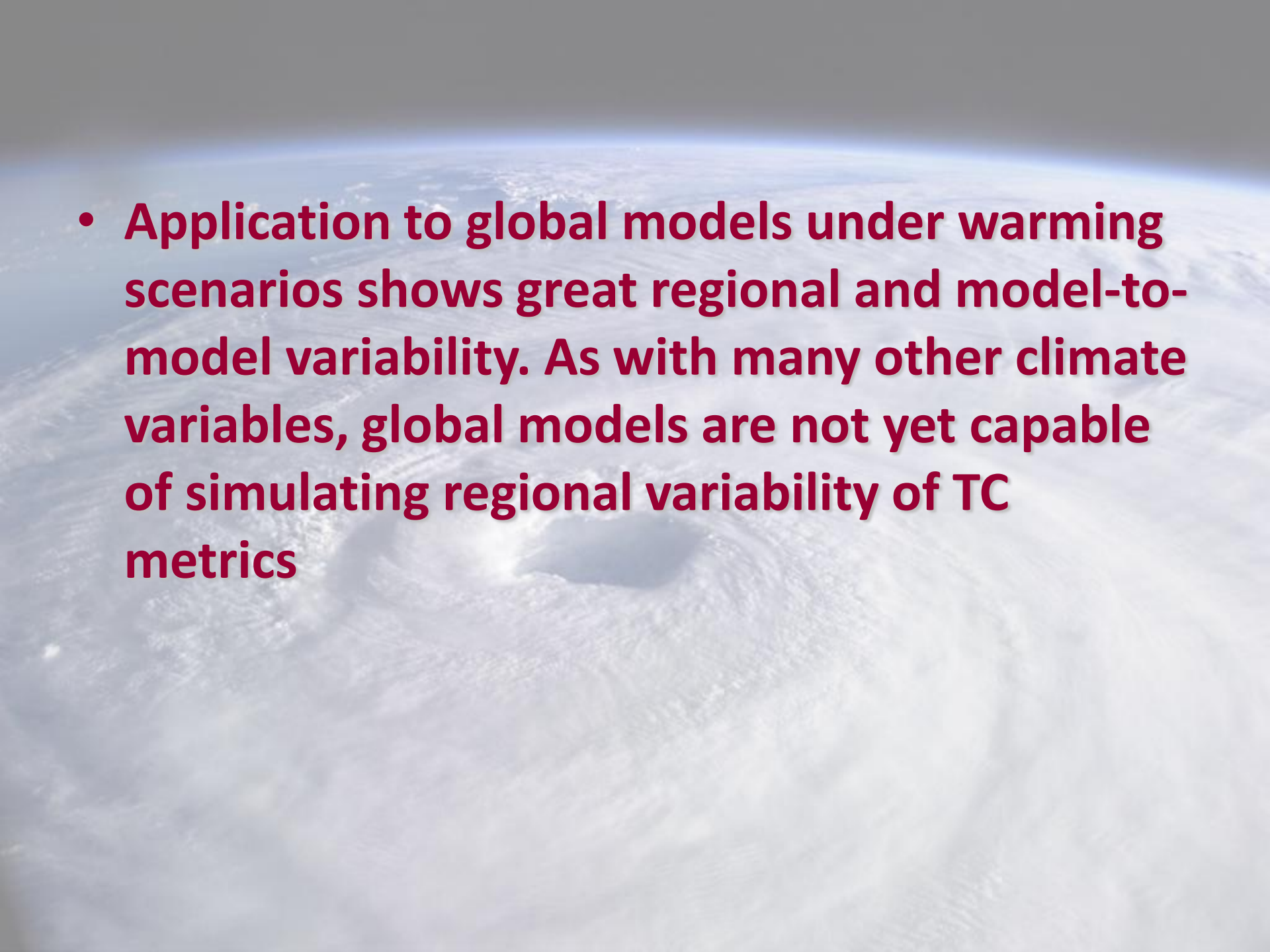
Couple Hurricane Model to Storm Surge Model (ADCIRC) Results for the Battery, New York City

ADCIRC simulation for Battery, NY, for 1thNYHurr12116-ro1200
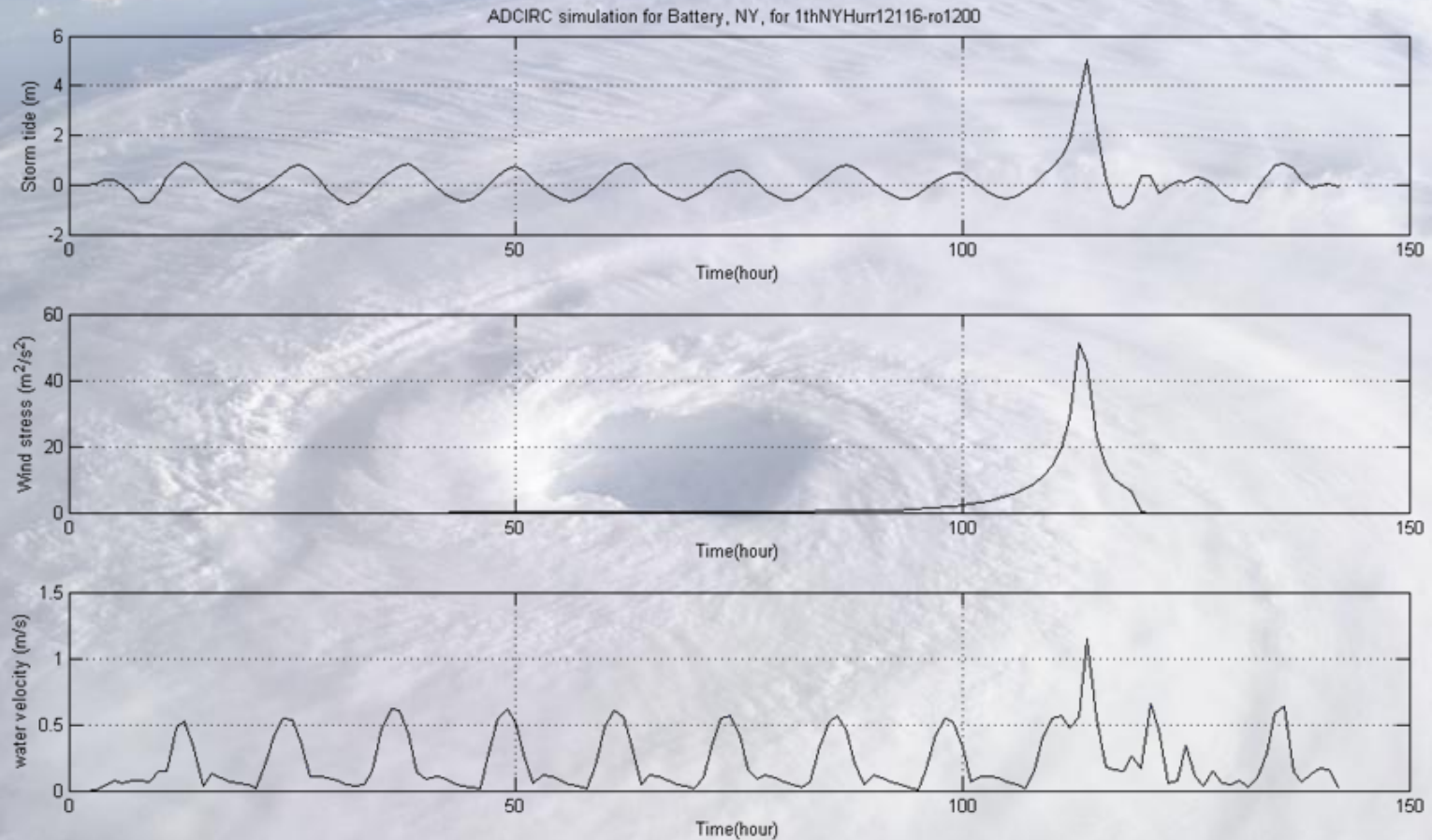
Summary:

- **Global (and most regional) models are far too coarse to simulate reasonably intense tropical cyclones**

- **Globally and regionally simulated tropical cyclones are not coupled to the ocean**

- We have developed a technique for downscaling global models or reanalysis data sets, using a very high resolution, coupled TC model phrased in angular momentum coordinates

- Model shows high skill in capturing spatial and seasonal variability of TCs, has an excellent intensity spectrum, and captures well known climate phenomena such as ENSO and the effects of warming over the past few decades

- **Application to global models under warming scenarios shows great regional and model-to-model variability. As with many other climate variables, global models are not yet capable of simulating regional variability of TC metrics**